The Effects of Nuclear Weapons

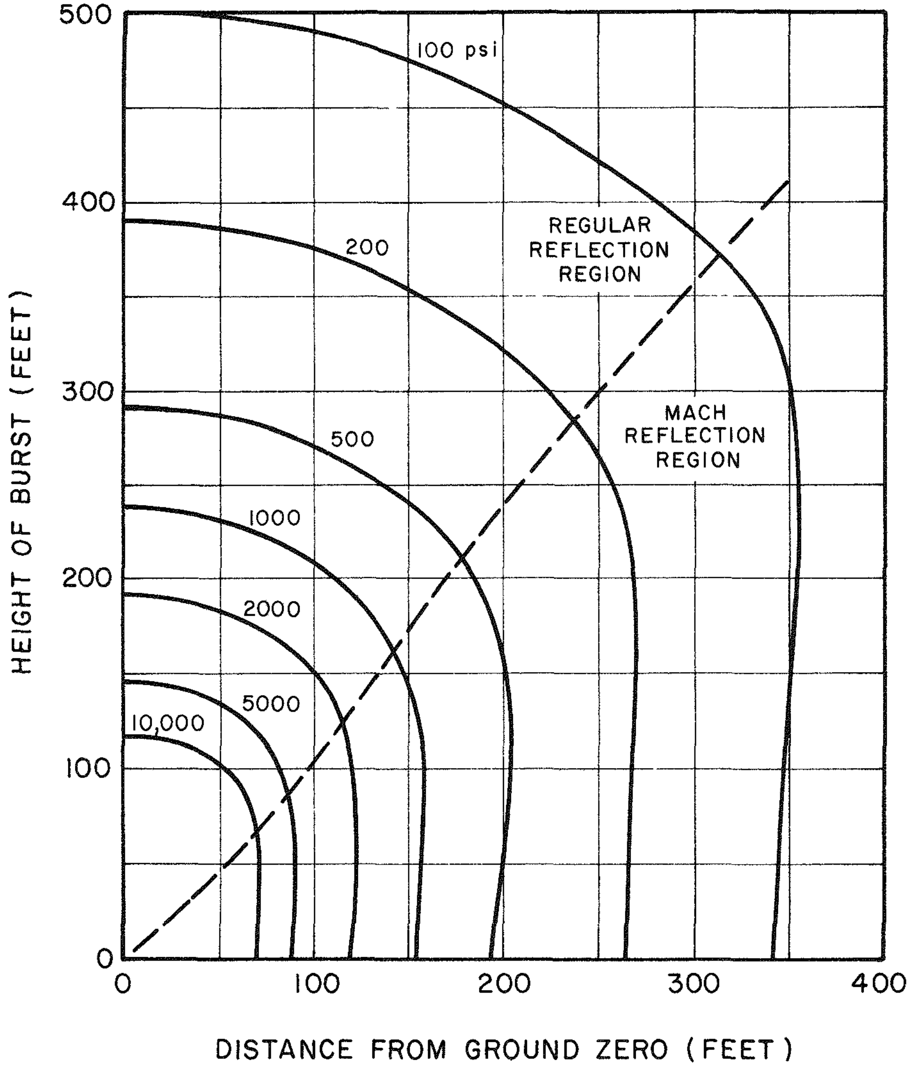

Figure 3.73a. Peak overpressures on the ground for a 1-kiloton burst (high-pressure range).

The curves in Fig. 3.73b show peak overpressures on the ground in the intermediate-pressure range as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The broken line separates the regular reflection region from the Mach region and indicates where the triple point is formed (§ 3.24 *et seq.*). The data are considered appropriate for nearly ideal surface conditions. (For terrain, surface, and meteorological effects, see (§ 3.35–3.43, § 3.47–3.49, and § 3.79 *et seq.*).

Scaling. The height of burst and the distance from ground zero to which a given peak overpressure extends scale as the cube root of the yield, i.e.,

$$\frac{d}{d_1} = \frac{h}{h_1} = W^{1/3},$$

where, for a given peak overpressure, d_1 and h_1 are distance from ground zero and height of burst for 1 KT, and d and h are the corresponding distance and height of burst for W KT. For a height of burst of 5,000 feet or less, a homogeneous sea-level atmosphere may be assumed.

Example

Given: A 100 KT detonation at a height of 2,320 feet.

Find: The peak overpressure at 1,860 feet from ground zero.

Solution: The corresponding height of burst for 1 KT is

$$h_1 = \frac{h}{W^{1/3}} = \frac{2{,}320}{(100)^{1/3}} = 500 \text{ feet.}$$

and the ground distance is

$$d_1 = \frac{d}{W^{1/3}} = \frac{1{,}860}{(100)^{1/3}} = 400 \text{ feet.}$$

From Fig. 3.73b, at a ground distance of 400 feet and a burst height of 500 feet, the peak overpressure is 50 psi. *Answer.*

The procedure described above is applicable to similar problems for the curves in Figs. 3.73a and c.

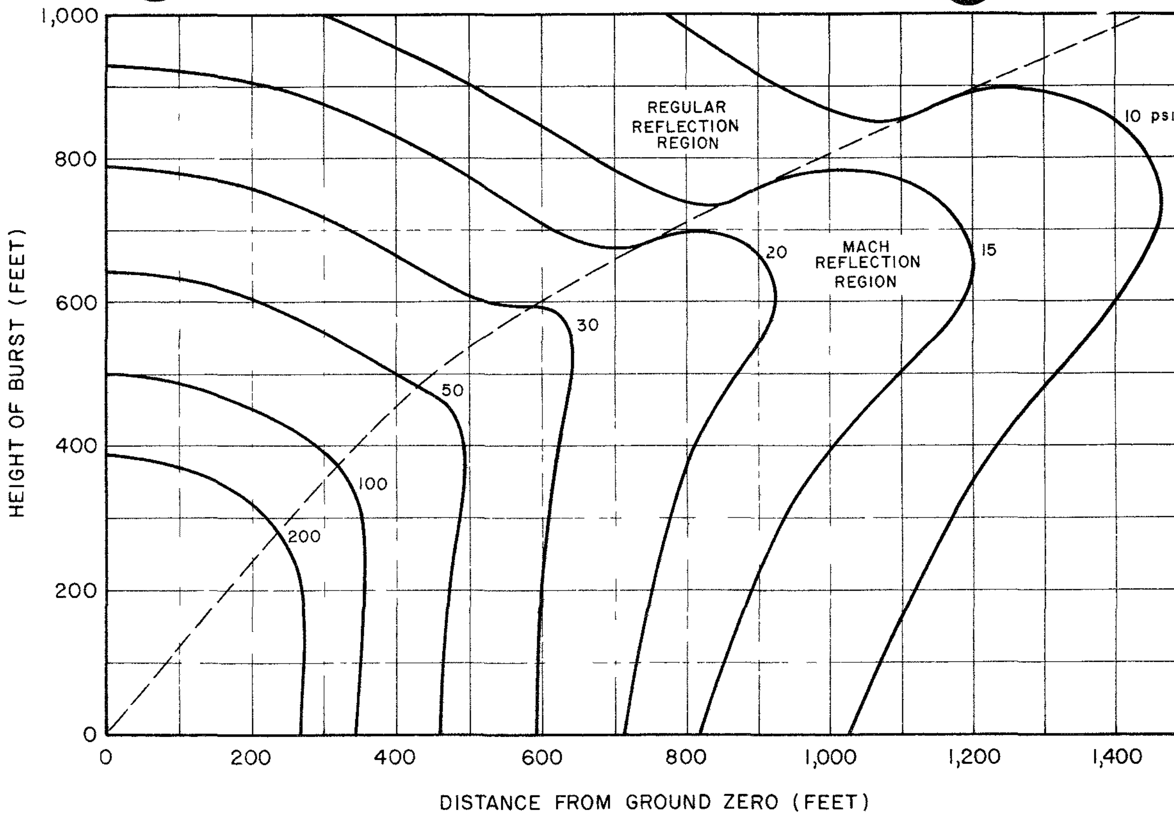

Figure 3 73b. Peak overpressures on the ground for a 1-kiloton burst (intermediate-pressure range).

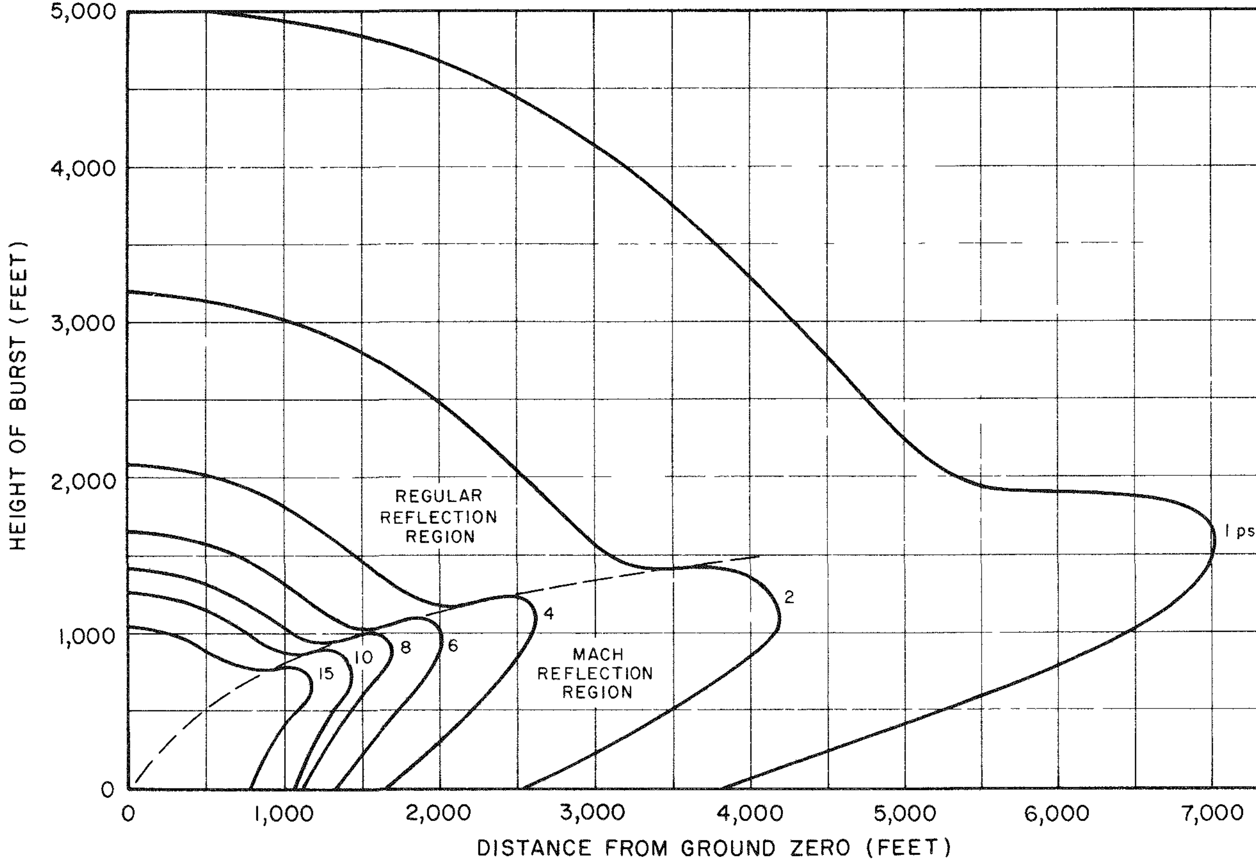

Figure 3.73c. Peak overpressures on the ground for 1-kiloton burst (low-pressure range).

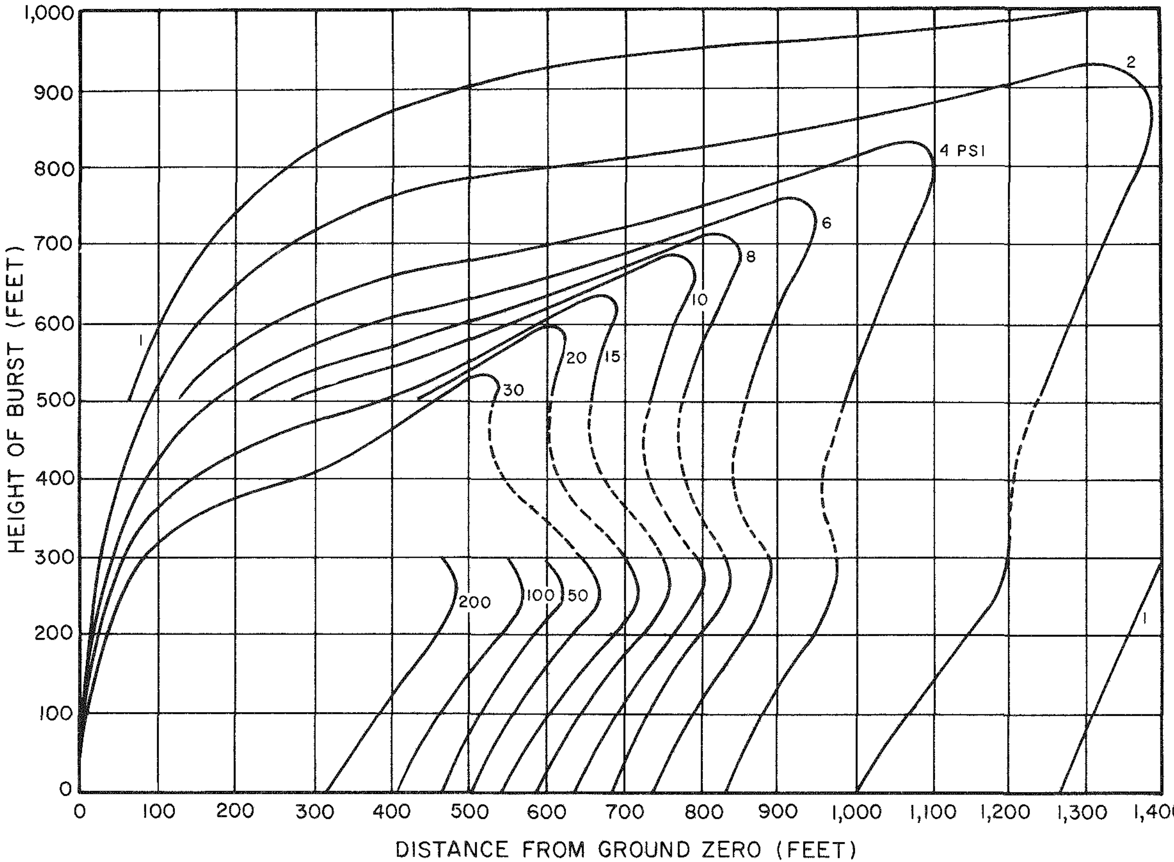

Figure 3.75. Horizontal component of peak dynamic pressure for 1-kiloton burst.

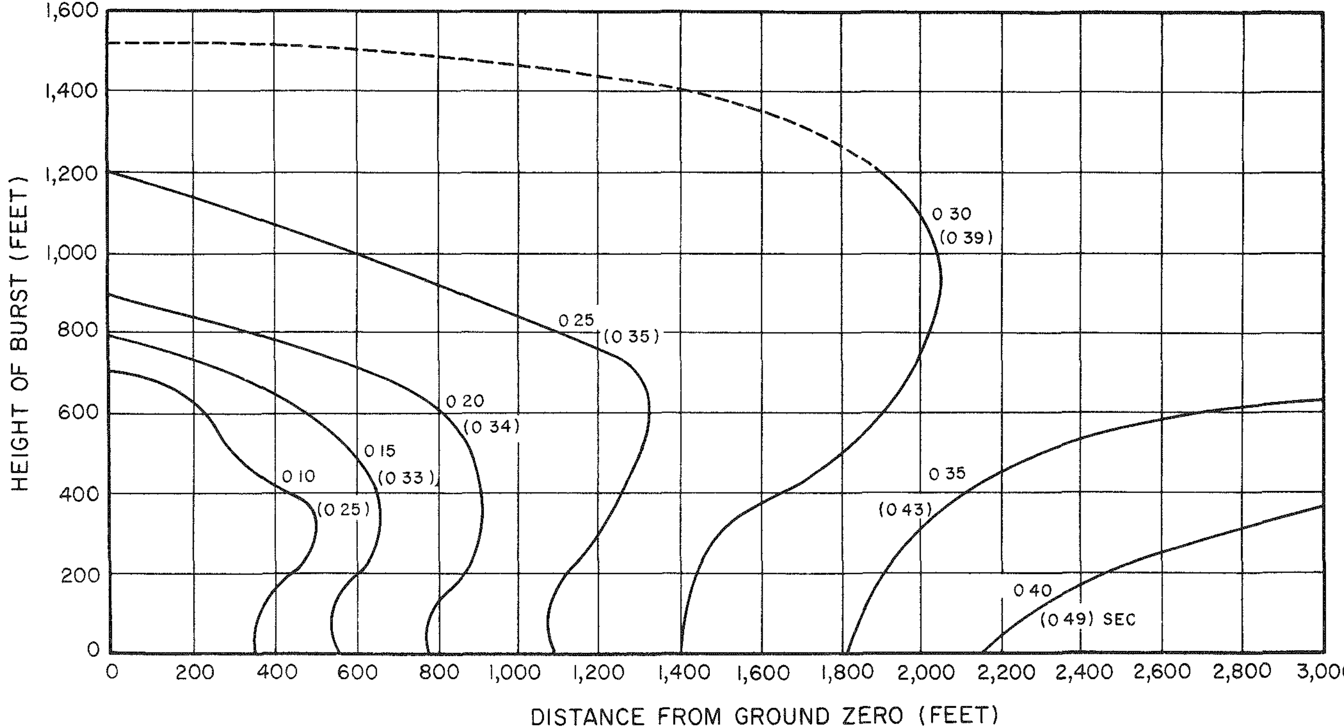

Figure 3 76 Positive phase duration on the ground of overpressure and dynamic pressure (in parentheses) for 1-kiloton burst

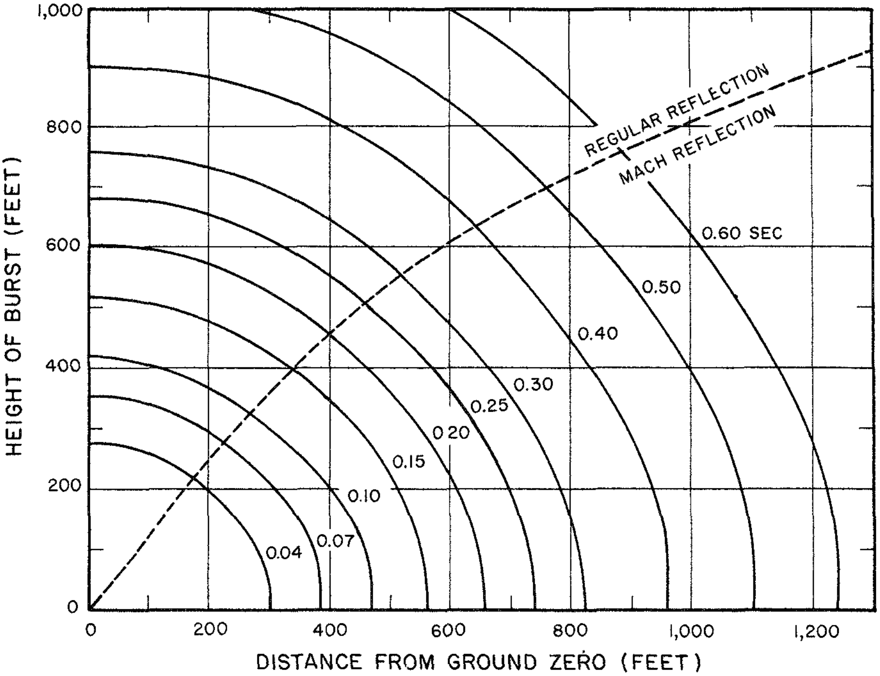

Figure 3.77a. Arrival times on the ground of blast wave for 1-kiloton burst (early times).

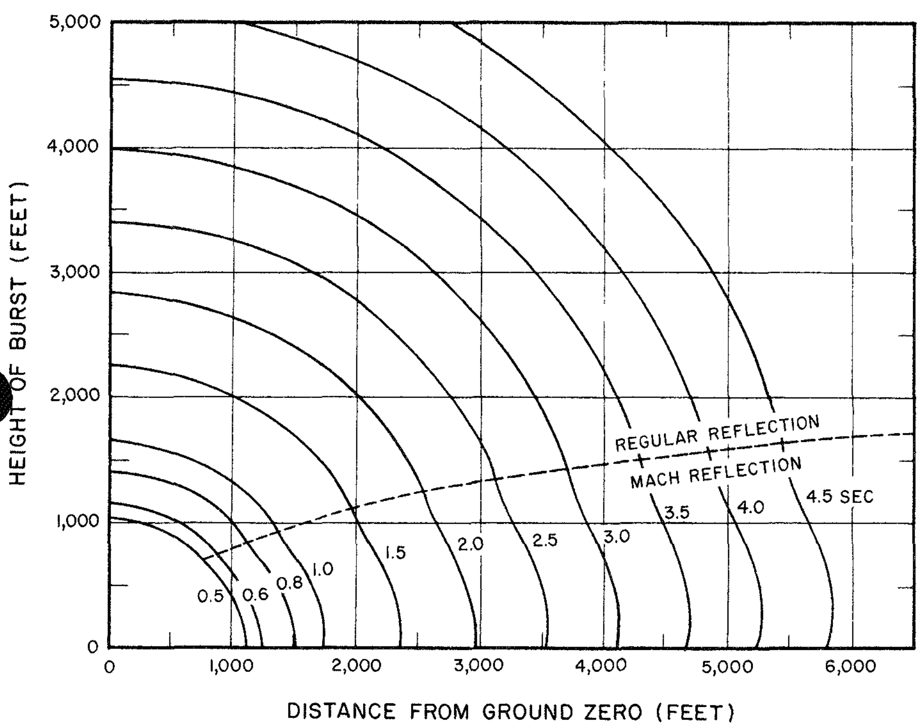

Figure 3.77b. Arrival times on the ground of blast wave for 1-kiloton burst (late times).

nents of the loads over the two areas and then subtract them. In practice, an approximation may be used to obtain the required result in such cases where the net horizontal loading is considered to be important. It may be pointed out that, in certain instances, especially for large structures, it is the local loading, rather than the net loading, which is the significant criterion of damage.

4.66 In the approximate procedure for determining the net loading, the overpressure loading during the diffraction stage is considered to be equivalent to an initial impulse equal to $p_r A(2H/U)$, where A is the projected area normal to the direction of the blast propagation. It will be noted that $2H/U$ is the time taken for the blast front to traverse the structure. The net drag coefficient for a single cylinder is about 0.4 in the blast pressure range of interest (§ 4.23). Hence, in addition to the initial impulse, the remainder of the net horizontal loading may be represented by the force 0.4 $q(t)A$, as seen in Fig. 4.66, which applies to a single structure. When a frame is made up of a number of circular elements, the methods used are similar to those for an open frame structure (§ 4.55) with C_d equal to 0.2.

NONIDEAL BLAST WAVE LOADING

4.67 The preceding discussions have dealt with loading caused by blast waves reflected from nearly ideal ground surfaces (§ 3.47). In practice, however, the wave form will not always be ideal. In particular, if a precursor wave is formed (§ 3.79 *et seq.*), the loadings may depart radically from

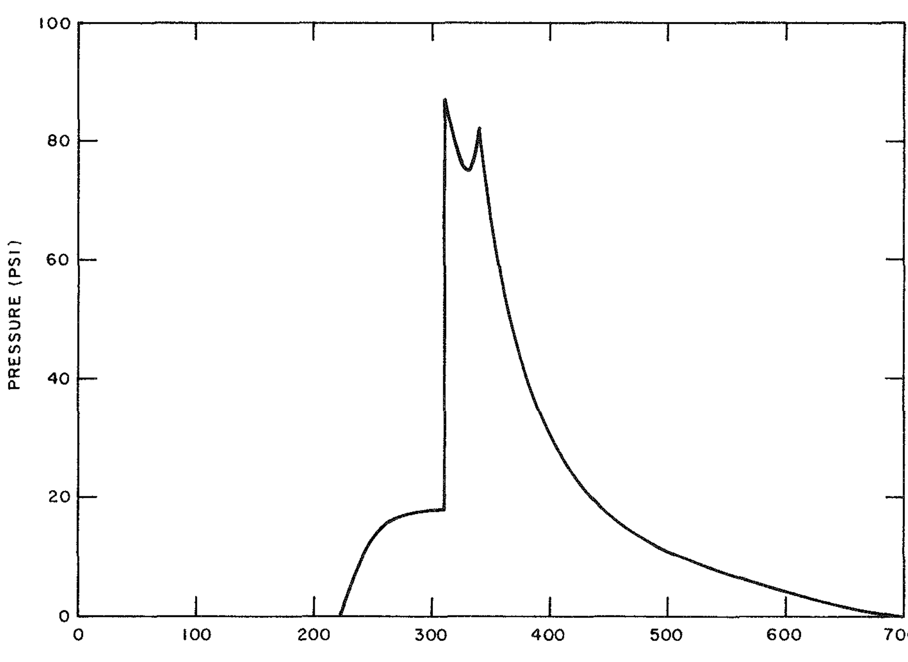

Figure 4.67a. Nonideal incident air blast (shock) wave.

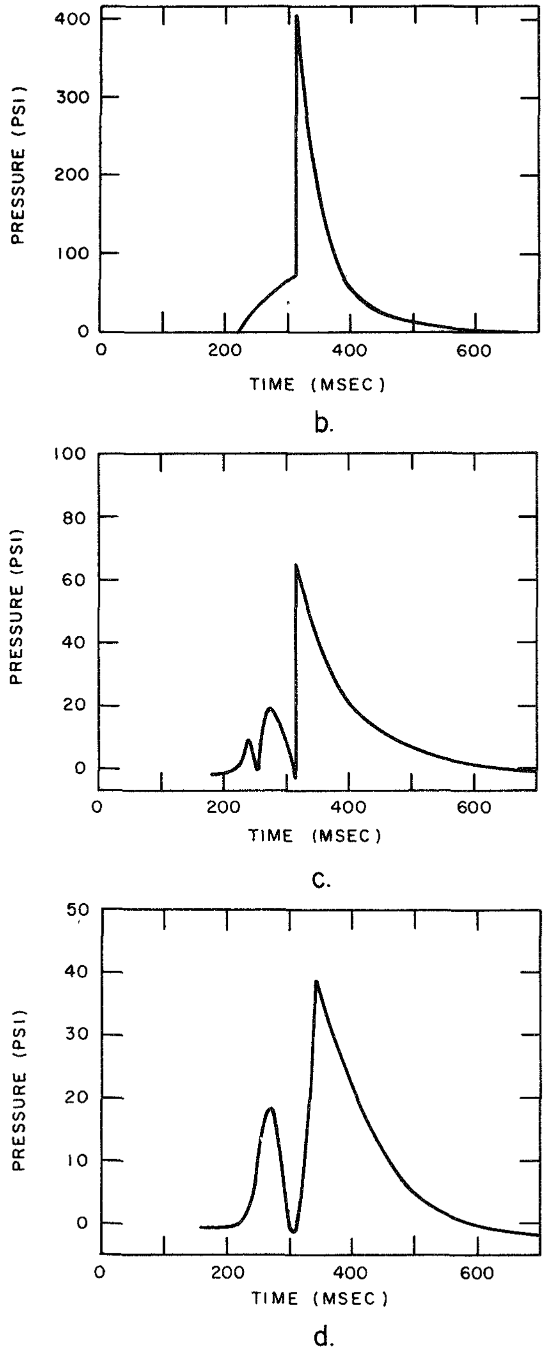

Figure 4.67b, c, d. Loading pattern on the front, top, and back, respectively, on a rectangular block from nonideal blast wave.

those described above. Although it is beyond the scope of the present treatment to provide a detailed discussion of nonideal loading, one qualitative example is given here. Figure 4.67a shows a nonideal incident air blast (shock) wave and Figs. 4.67b, c, and d give the loading patterns on the front, top, and back, respectively, of a rectangular block as observed at a nuclear weapon test. Comparison of Figs. 4.67b, c, and d with the corresponding Figs. 4.42, 4.43, and 4.44 indicates the departures from ideal loadings that may be encountered in certain circumstances. The net loading on this structure was significantly less than it would have been under ideal conditions, but this would not necessarily always be the case.

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*These documents may be purchased from the National Technical Information Service, U S Department of Commerce, Springfield, Virginia 22161

Figure 5.20a. Upper photo: Reinforced-concrete, aseimic structure; window fire shutters were blown in by blast and the interior gutted by fire (0.12 mile from ground zero at Hiroshima). Lower photo: Burned out interior of similar structure.

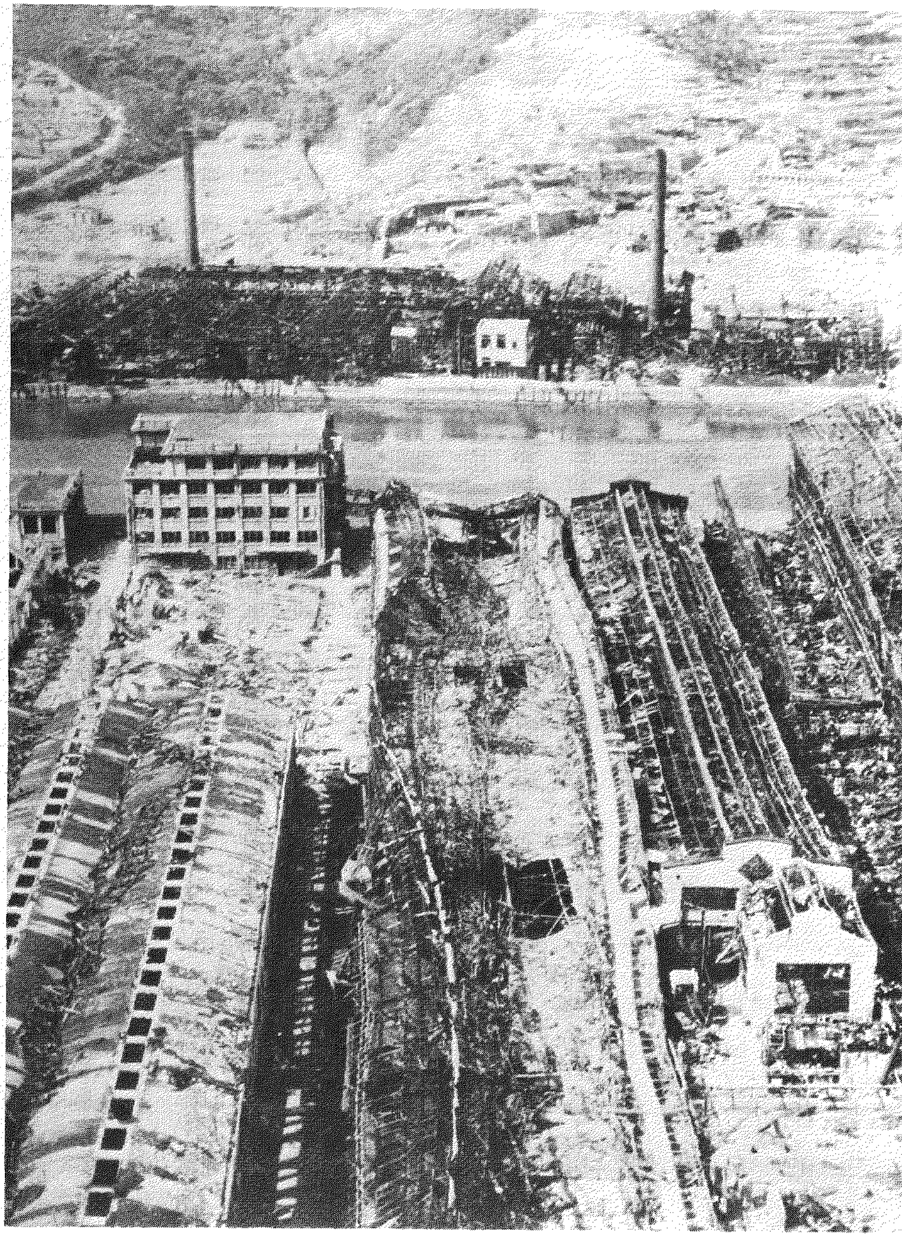

Figure 5.25. At left and back of center is a multistory, steel-frame building (0.85 mile from gound zero at Nagasaki).

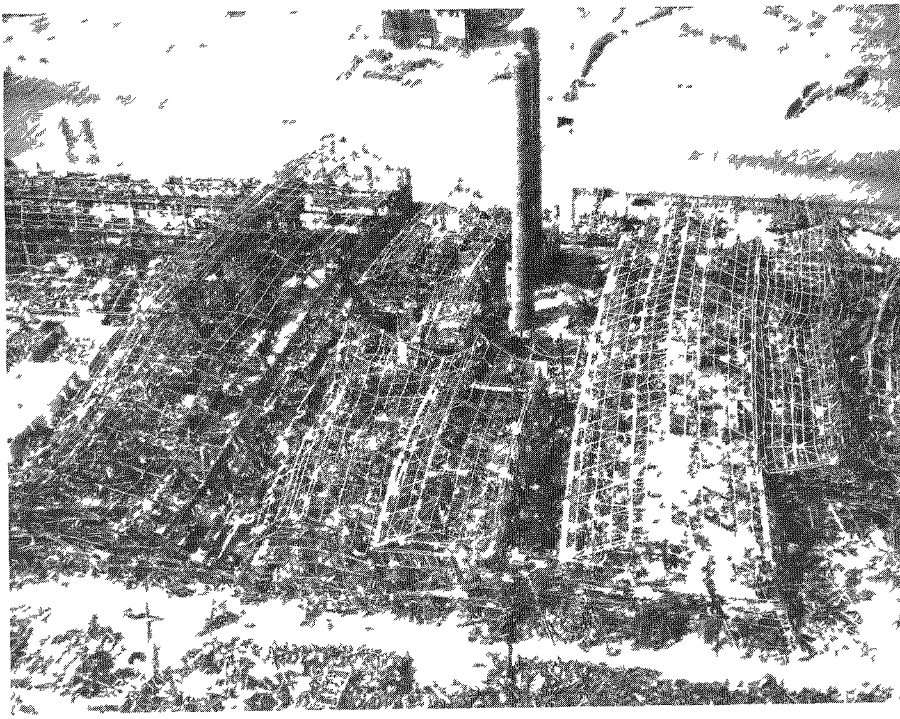

Figure 5 34a Destroyed ındustrıal area showıng smokestacks stıll standıng (0 51 mıle from ground zero at Nagasaki)

remained standing, but was badly distorted and pulled away from the concrete footings. On the side facing the explosion the deflection was about 1 foot at the eaves (Fig. 5.37b)

5.38 At a peak overpressure of 1.3 pounds per square inch the main steel frame suffered only slight distortion. The aluminum roofing and siding were not blown off, although the panels were disengaged from the bolt fasteners on the front face of the steel columns and girts (horizontal connecting members) Wall and roof panels facing the explosion were dished inward. The center girts were torn loose from their attachments to the columns ın the front of the buılding. The aluminum panels on the side walls were dished inward slightly, but on the rear wall and rear slope of the roof, the sheeting was almost undisturbed.

5.39 As presently designed, structures of this type may be regarded as being repairable, provided they are not exposed to blast pressures exceeding 1 pound per square inch. Increased blast resistance would probably result from improvement in the design of girts and purlins (horizontal members supporting rafters), in particular. Better fastening between sill and wall footing and increased resistance to transverse loading would also be beneficial

Figure 5.76. Reinforced masonry-block house before a nuclear explosion, Nevada Test Site.

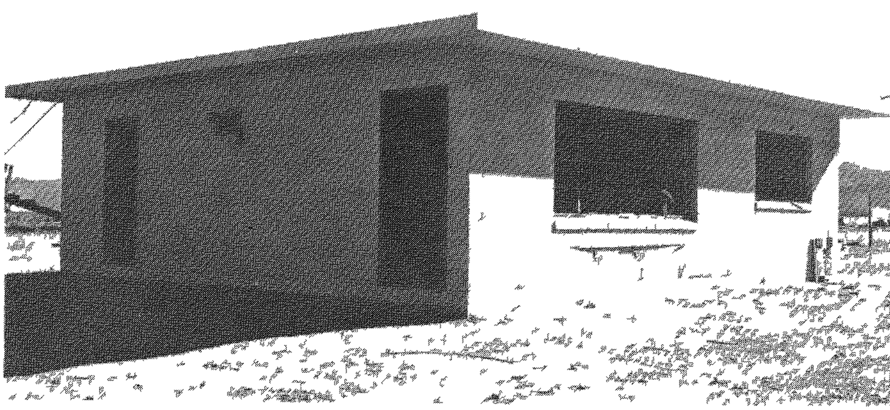

Figure 5.77. Reinforced masonry-block house after a nuclear explosion (5 psi peak overpressure).

column in the center span of the window.

5.79 A house of the same type exposed to the blast at a peak overpressure of 1.7 pounds per square inch suffered little more than the usual destruction of doors and windows. The steel window-sash remained in place but was distorted, and some spalling of the concrete around lug connections was noted. On the whole, the damage to the house was of a minor character and it could readily have been repaired.

Figure 5 89. Truck broadside to the blast wave (5 psi peak overpressure) overturned, electric utility truck in background head-on to blast was damaged but remained standing

from the blast by the design of the truck body or when housed in compartments with strong doors

RAILROAD EQUIPMENT

5.92 Railroad equipment suffered blast damage in Japan and also in tests in Nevada. Like motor vehicles, these targets are primarily drag sensitive and damage cannot be directly related to overpressure At a peak overpressure of 2 pounds per square inch from a kiloton-range weapon, an empty wooden boxcar may be expected to receive relatively minor damage. At 4 pounds per square inch overpressure, the damage to a loaded wooden boxcar would be more severe (Fig. 5.92a). At a peak overpressure of 6 pounds per square inch the body of an empty wooden boxcar, weighing about 20 tons, was lifted off the trucks, i.e., the wheels, axles, etc., carrying the body, and landed about 6 feet away The trucks themselves were pulled off the rails, apparently by the brake rods connecting them to the car body. A similar boxcar, at the same location, loaded with 30 tons of sandbags remained upright (Fig. 5.92b). Although the sides were badly damaged and the roof demolished, the car was capable of being moved on its own wheels At 7.5 pounds per square inch peak overpressure, a loaded boxcar of the same type was overturned, and at 9 pounds per square inch it was completely demolished

5.93 A Diesel locomotive weighing 46 tons was exposed to a peak over-

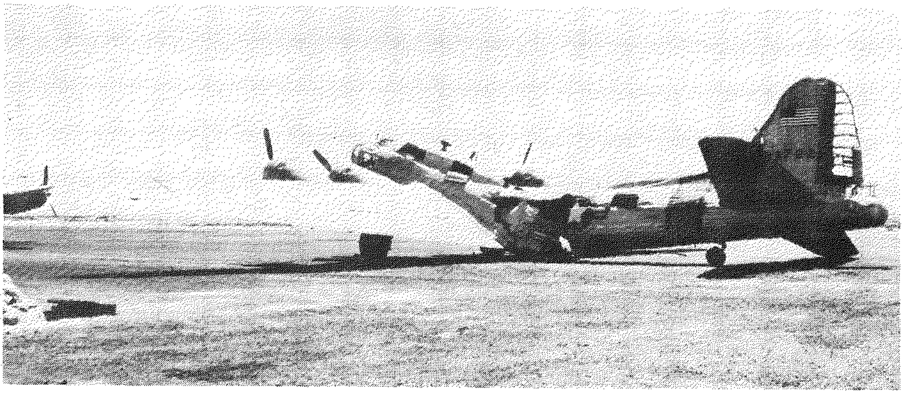

Figure 5.95a. Aircraft after side exposed to a nuclear explosion (3.6 psi peak overpressure).

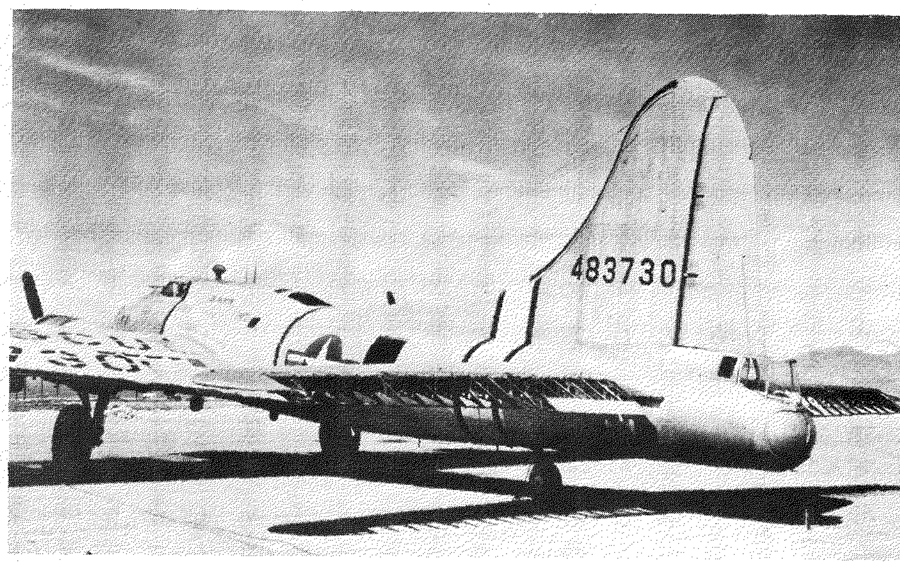

Figure 5.95b. Aircraft after tail exposed to a nuclear explosion (2.4 psi peak overpressure).

UTILITIES

ELECTRICAL DISTRIBUTION SYSTEMS

5.98 Because of the extensive damage caused by the nuclear explosions to the cities in Japan, the electrical distribution systems suffered severely. Utility poles were destroyed by blast or fire, and overhead lines were heavily damaged at distances up to 9,000 feet (1.7 miles) from ground zero (Fig. 5.98).

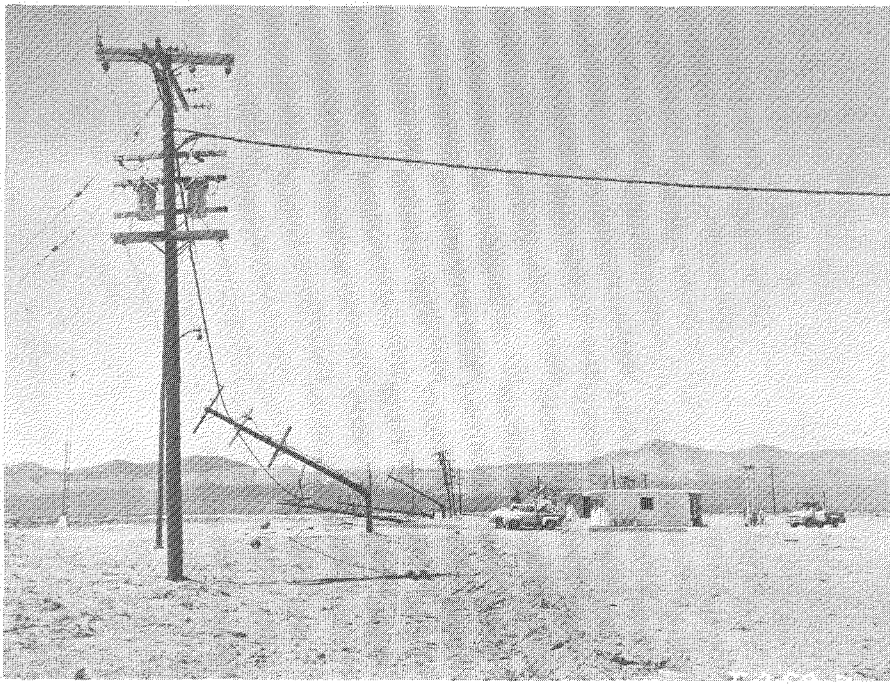

Figure 5.104. Collapse of utility poles on line (5 psi peak overpressure, 0.6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site.

were unharmed. Although the pole line would have required some rebuilding, the general damage was such that it could have been repaired within a day or so with materials normally carried in stock by electric utility companies.

GAS, WATER, AND SEWERAGE SYSTEMS

5.106 The public utility system in Nagasaki was similar to that of a somewhat smaller town in the United States, except that open sewers were used. The most significant damage was suffered by the water supply system, so that it became almost impossible to extinguish fires. Except for a special case, described below, loss of water pressure resulted from breakage of pipes inside and at entrances to buildings or on structures, rather than from the disruption of underground mains (Figs. 5.106a and b). The exceptional case was one in which the 12-inch cast iron water pipes were 3 feet below grade in a filled-in area. A number of depressions, up to 1 foot in depth, were produced in the fill, and these caused failure of the underground pipes, presumably due to unequal displacements.

5.107 There was no appreciable damage to reservoirs and water-treatment plants in Japan. As is generally the case, these were located outside the cities, and so were at too great a distance from the explosions to be damaged in any way.

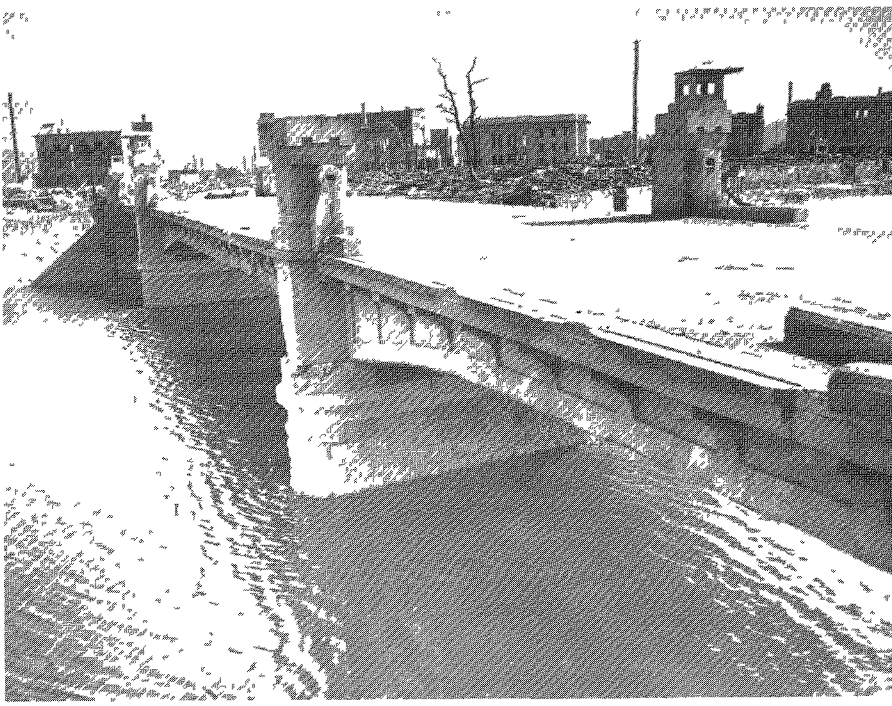

Figure 5.127a. Bridge with deck of reinforced concrete on steel-plate girders; outer girder had concrete facing (270 feet from ground zero at Hiroshima). The railing was blown down but the deck received little damage so that traffic continued.

at greater distances from ground zero, suffered more lateral shifting. A reinforced-concrete deck was lifted from the supporting steel girder of one bridge, apparently as a result of reflection of the blast wave from the surface of the water below.

HEAVY-DUTY MACHINE TOOLS

5.128 The vulnerability of heavy-duty machine tools and their components to air blast from a nuclear explosion was studied at the Nevada Test Site to supplement the information from Nagasaki (§ 5.33). A number of machine tools were anchored on a reinforced-concrete slab in such a manner as to duplicate good industrial practice. Two engine lathes (weighing approximately 7,000 and 12,000 pounds, respectively), and two horizontal milling machines (7,000 and 10,000 pounds, respectively) were exposed to a peak overpressure of 10 pounds per square inch. A concrete-block wall, 8 inches thick and 64 inches high, was constructed immediately in front of the machines, i.e., between the machines and ground zero (Fig. 5.128). The purpose of this wall was to simulate the exterior wall of the average industrial plant and to provide debris and missiles.

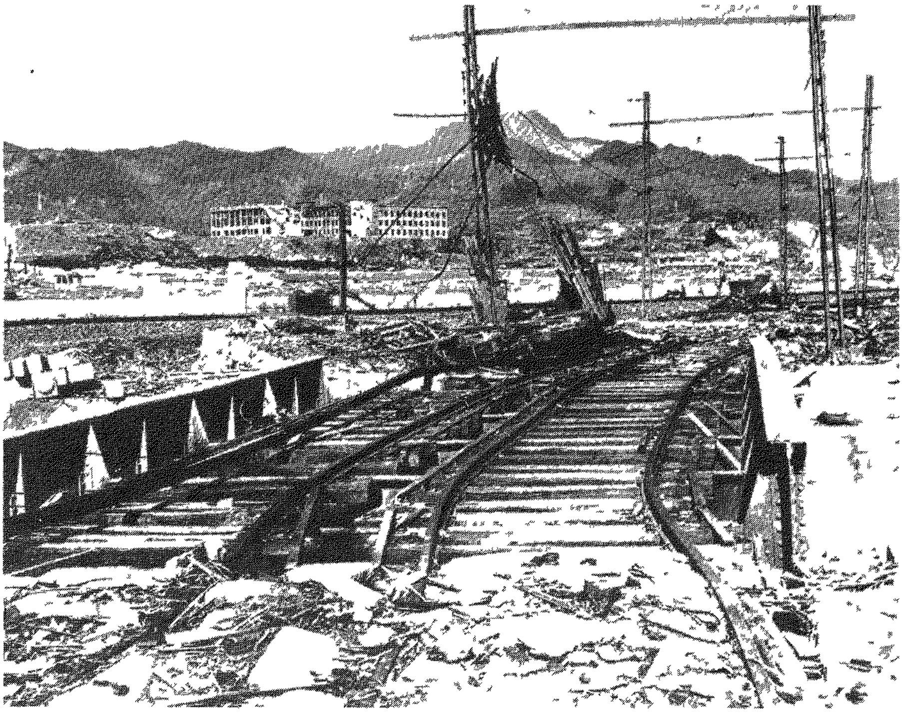

Figure 5 127b A steel-plate girder, double-track railway bridge (0 16 mile from ground zero at Nagasaki) The plate girders were moved about 3 feet by the blast, the railroad track was bent out of shape and trolley cars were demolished, but the poles were left standing

5.129 Of the four machines, the three lighter ones were moved from their foundations and damaged quite badly (Fig 5 129a). The fourth, weighing 12,000 pounds, which was considered as the only one to be actually of the heavy-duty type, survived (Fig. 5.129b). From the observations it was concluded that a properly anchored machine tool of the true heavy-duty type would be able to withstand peak overpressures of 10 pounds per square inch or more without substantial damage

5.130 In addition to the direct effects of blast, considerable destruction was caused by debris and missiles, much of which resulted from the expected complete demolition of the concrete-block wall. Delicate mechanisms and appendages, which are usually on the exterior and unprotected, suffered especially severely Gears and gear cases were damaged, hand valves and control levers were broken off, and drive belts were broken. It appears, however, that most of the missile damage could be easily repaired if replacement parts were available, since major dismantling would not be required.

5.131 Behind the two-story brick house in the peak overpressure region of 5 pounds per square inch (§ 5 67), a

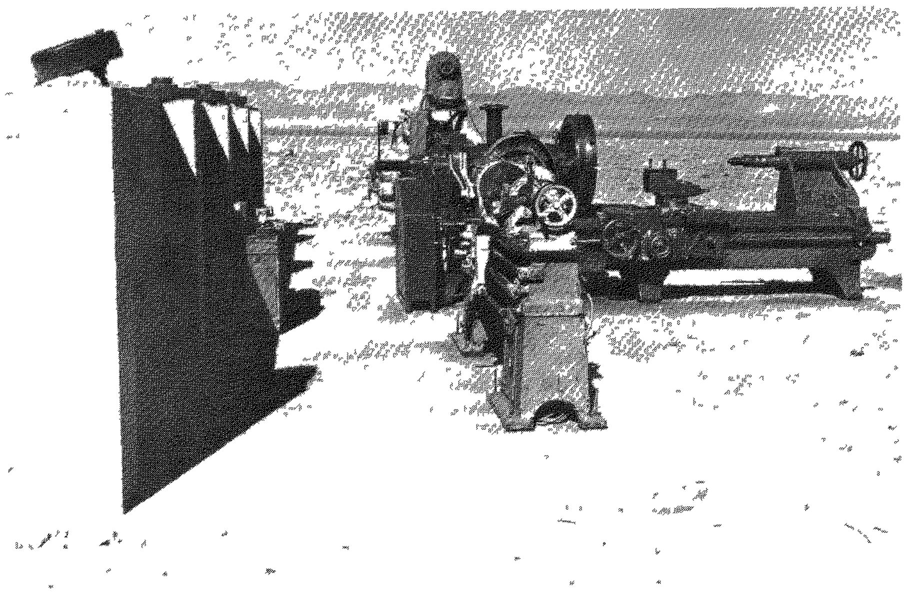

Figure 5.128. Machine tools behind masonry wall before a nuclear explosion, Nevada Test Site.

200-ton capacity hydraulic press weighing some 49,000 pounds was erected. The location was chosen as being the best to simulate actual factory conditions. This unusually tall (19 feet high) and slim piece of equipment showed little evidence of blast damage, even though the brick house was demolished. It was probable that the house provided some shielding from the blast wave. Moreover, at the existing blast pressure, missiles did not have high velocities. Such minor damage as was suffered by the machine was probably due to debris falling from the house.

5.132 At the 3-pounds per square inch peak overpressure location, there were two light, industrial buildings of standard type. In each of these was placed a vertical milling machine weighing about 3,000 pounds, a 50-gallon capacity, stainless-steel, pressure vessel weighing roughly 4,100 pounds, and a steel steam oven approximately 2½ feet wide, 5 feet high, and 9 feet long. Both buildings suffered extensively from blast, but the equipment experienced little or no operational damage. In one case, the collapsing structure fell on and broke off an exposed part of the milling machine.

5.133 The damage sustained by machine tools in the Nevada tests was probably less than that suffered in Japan at the same blast pressures (§ 5.33). Certain destructive factors, present in the latter case, were absent in the tests. First, the conditions were such that there was no damage by fire; and, second, there was no exposure to the elements after the explosion. In addition, the total amount of debris and missiles produced in the tests was probably less than in the industrial buildings in Japan.

Figure 5.129a. Machine tools after a nuclear explosion (10 psi peak overpressure).

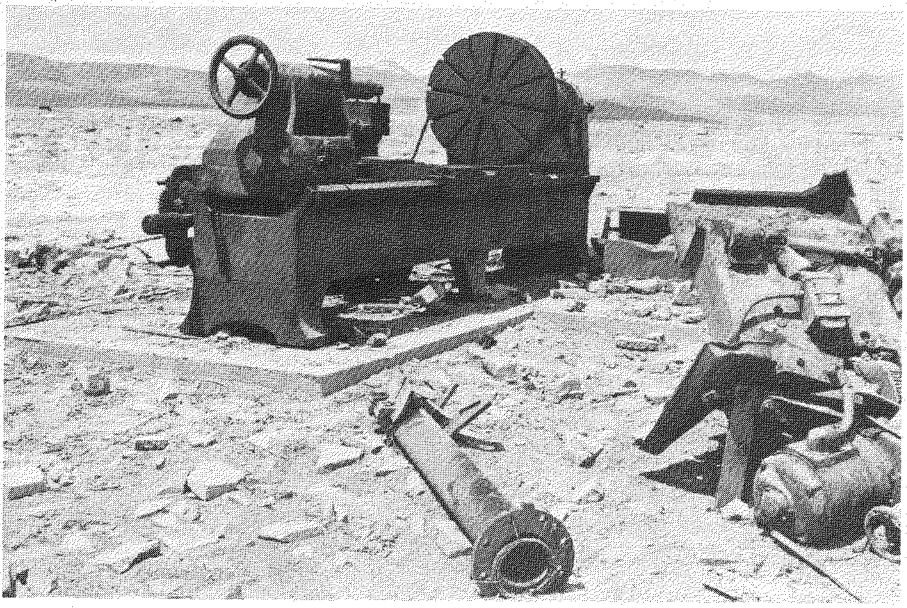

Figure 5.129b. Heavy-duty lathe after a nuclear explosion (10 psi peak overpressure).

will depend on a number of variables, including the structural characteristics, the nature of the soil, the depth of burial, and the downward pressure, i.e., the peak overpressure and direction of the blast wave. In Table 5.160 are given the limiting values of the peak overpressure required to cause various degrees of damage to two types of shallow buried structures. The range of pressures is intended to allow for differences in structural design, soil conditions, shape of earth mound, and orientation with respect to the blast wave.

5.161 Underground structures, buried at such a depth that the ratio of the burial depth to the span approaches (or exceeds) a value of 3.0, will obtain some benefit from the attenuation with depth of the pressure induced by air blast, and from the arching of the load from more deformable areas to less deformable ones. Limited experience at nuclear tests suggests that the arching action of the soil effectively reduces the loading on flexible structures.

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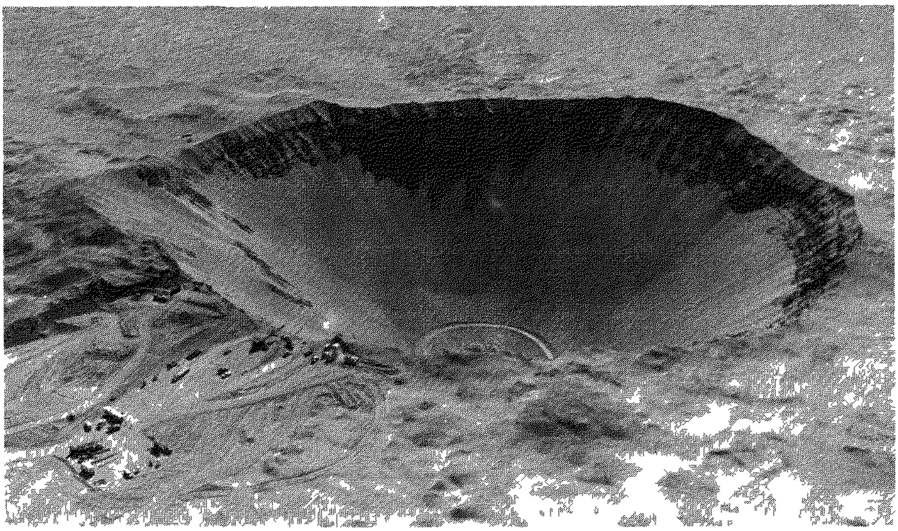

Figure 6.10 SEDAN event, crater formed by a 100-kiloton explosion in alluvial soil at the optimum depth of burst (635 feet) for cratering. The crater radius is 611 feet, the depth 323 feet, and the volume 179 million cubic feet

yield but the actual values depend on the soil characteristics.

6.09 For contact surface bursts, approximate values of the crater dimensions can be given. For a 1-kiloton nuclear explosion at the surface, the apparent radius of the crater in dry soil or dry soft rock is estimated to be about 60 feet. The radius at the crest of the lip will be 15 feet or so greater. The apparent depth of the crater is expected to be about 30 feet. In hard rock, consisting of granite or sandstone, the dimensions will be somewhat less. The radius will be appreciably greater in soil saturated with water, and so also will be the initial depth, to which structural damage is related. The final depth, however, will be shallower because of "hydraulic fill," i.e., slumping back of wet material and the seepage of water carrying loose soil. All crater dimensions resulting from a surface burst of yield W kilotons are related approximately to those given above for a yield of 1-kiloton by the factor $W^{0.3}$. For example, for a 100-kiloton explosion on the surface of dry soil, the radius of the crater may be expected to be roughly $60 \times (100)^{0.3} = 240$ feet, and the depth about $30 \times (100)^{0.3} = 120$ feet. Further information on crater dimensions will be found in § 6.72 *et seq.*

6.10 As the depth of burial is increased, the radius and depth of the crater also increase until maxima are reached; deeper burial then results in progressively smaller craters. These maximum values of radius and depth for a given yield are termed "optimum" (Fig. 6.06d) and depths of burial for optimum crater radius and for optimum crater depth are roughly equal. A photograph of a crater formed at the optimum burst depth is shown in Fig. 6.10. For a 1-kiloton weapon, the

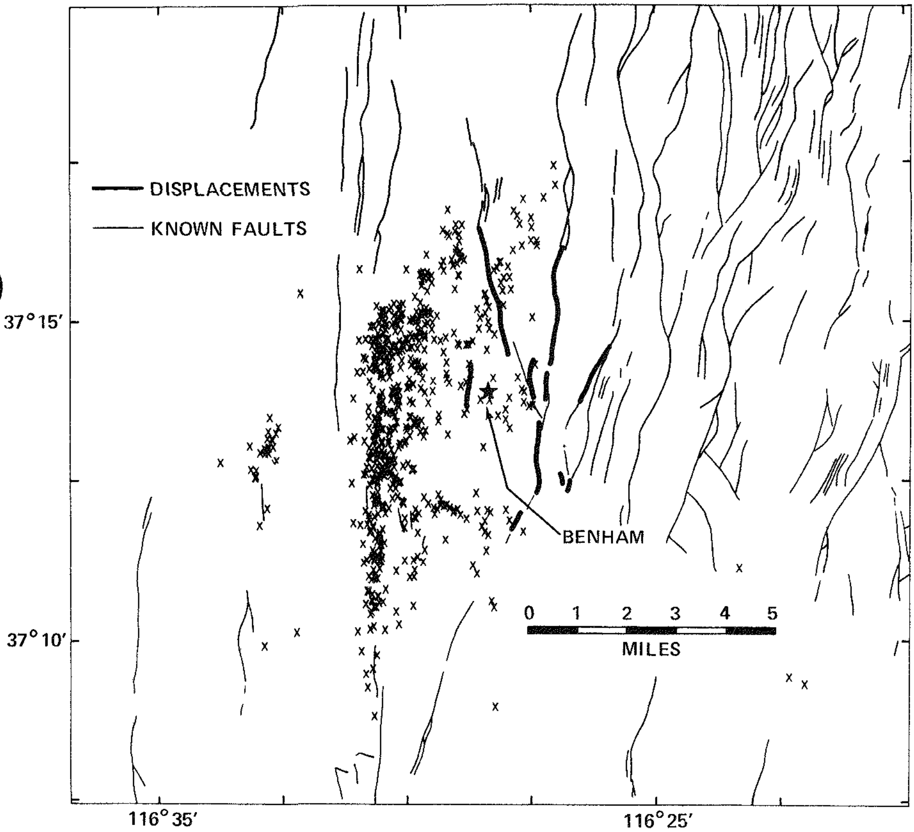

Figure 6.21. Locations of 640 aftershocks and fault displacements from the BENHAM 1.1-megaton test.

6.22 As may be seen from Fig. 6.21, most of the ground displacements in the vicinity of the BENHAM explosion occurred along or near pre-existing fault lines. The maximum vertical displacement was 1.5 feet, at locations 1.5 and 2.5 miles north of the burst point. Larger displacements have occurred in some instances, but vertical displacements of the surface along or near fault lines have been mostly less than a foot. These displacements, although not continuous, may extend for a distance of several miles. For the same (or similar) conditions, the linear extent of displacement is roughly proportional to the yield of the explosion.

6.23 A rough rule of thumb has been developed from observations at the Nevada Test Site. According to this rule, displacement along a fault line may occur only if the distance (in feet) from surface zero is less than about 1000 times the cube root of the energy expressed in kilotons of TNT equivalent. Thus, for a 1-megaton (1000-kiloton) detonation, displacement would be expected only if the fault lines were within a distance of roughly $1000 \times (1000)^{1/3} = 1000 \times 10 = 10{,}000$ feet

Figure 6 55 Waves from the BAKER underwater explosion reaching the beach at Bikini, 11 miles from surface zero

Table 6.57

MAXIMUM HEIGHTS (CREST TO TROUGH) AND ARRIVAL TIMES OF WATER WAVES AT BIKINI BAKER TEST

Distance (yards)	330	660	1 330	2 000	2 700	3 300	4 000
Wave height (feet)	94	47	24	16	13	11	9
Time (seconds)	11	23	48	74	101	127	154

at the Bikini BAKER test A more generalized treatment of wave heights, which can be adapted to underwater explosions of any specified energy, is given in § 6 119 *et seq*

6.58 For the conditions that existed in the BAKER test, water wave damage is possible to ships that are moderately near to surface zero There was evidence for such damage to the carrier U S S Saratoga, anchored in Bikini lagoon almost broadside on to the explosion with its stern 400 yards from surface zero The ''island'' structure was

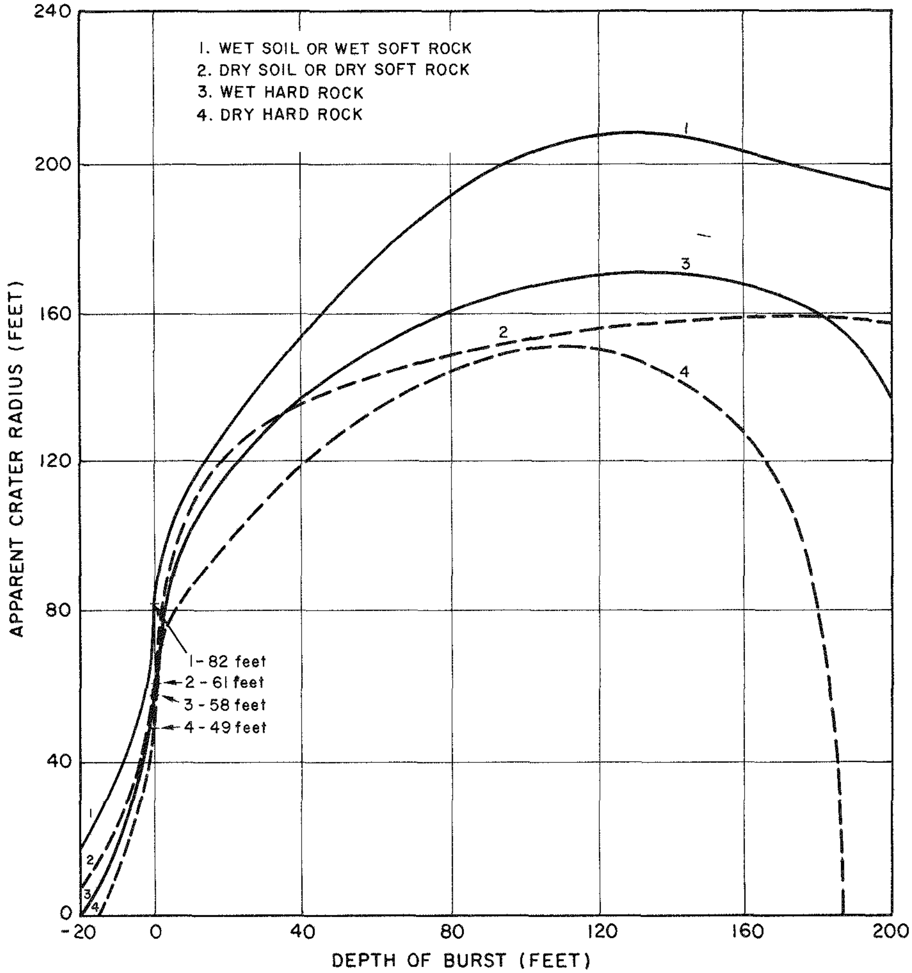

Figure 6.72a. Apparent crater radius as a function of depth of burst for a 1-kiloton explosion in (or above) various media.

CRATER EJECTA

6.73 Crater ejecta consist of soil or rock debris that is thrown beyond the boundaries of the apparent crater. Together with the fallback, which lies between the true and apparent crater boundaries, ejecta comprise all material completely disassociated from the parent medium by the explosion. The ejecta field is divided into two zones: (1) the crater lip including the continuous ejecta surrounding the apparent crater (Fig. 6.70), and (2) the discontinuous ejecta, comprising the discrete missiles that fall beyond the limit of the continuous ejecta.

6.74 The amount and extent of the continuous ejecta in the crater lip are

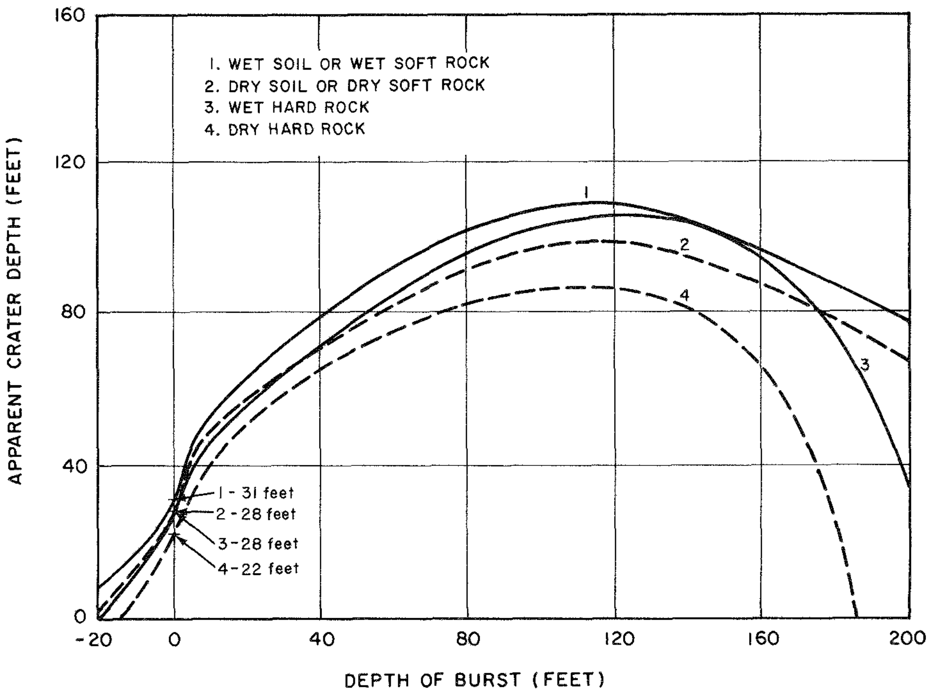

Figure 6.72b. Apparent crater depth as a function of depth of burst for a 1-kiloton explosion in (or above) various media.

determined primarily by the explosion yield and the location of the burst point, although the characteristics of the medium have some effect. The radial limit of the continuous ejecta, which is the outer edge of the lip, will usually vary from two to three times the apparent crater radius. In most cases, a satisfactory approximation to the radius of the continuous ejecta, R_e (Fig. 6.70), is

$$R_e \approx 2.15 R_a.$$

6.75 The depth of the ejecta decreases rapidly in an exponential manner as the distance from surface zero increases. In general, about 80 to 90 percent of the entire ejecta volume is deposited within the area of the continuous ejecta. Analysis of data for craters formed by nuclear bursts in soil indicates that ejecta mass represents approximately 55 percent of the apparent crater mass (the remainder being found in fallback, compaction, and the dust cloud which is blown away). For an explosion of given yield, the ejecta mass increases significantly with the depth of burst until the optimum depth is reached. Ejecta thickness can be estimated for soil in terms of the apparent radius and diameter; thus:

$$t_e \approx 0.9 D_a \left(\frac{R_a}{R}\right)^{3.86}, \text{ for } R > 1.8 R_a, \quad (6.75.1)$$

where t_e is the ejecta thickness and R is the distance from surface zero to the point of interest. In equation (6.75.1), it is assumed that the ejecta mass density is approximately equal to the original in-situ density of the medium, which could be considered valid for a soil medium. However, the bulking inherent in disturbed rock media would result in ejecta thicknesses about 30 percent greater than predicted by equation (6.75.1).

GEOLOGIC FACTORS

6.76 In addition to the nature and water content of the soil, certain other geologic factors may influence crater size and shape. Terrain slopes of about 5° or more will affect the geometry of a crater formed by either surface or buried explosions, with the influence of the slope being more evident as burst depth increases. The surface slope will cause much of the debris ejected by the explosion to fall on the downslope side of the crater, often resulting in rockslides below the crater area. In addition, the upslope rupture zone may collapse into the crater, resulting in an asymmetric crater shape.

6.77 In rock, the dip of bedding planes will influence energy propagation, causing the maximum crater depth to be offset in the down-dip direction. Little overall effect is noted in regard to crater radius, but differences in ejecta angles cause the maximum lip height and ejecta radius to occur in the down-dip direction.

6.78 A subsurface groundwater table in a soil medium will begin to influence the size and shape of the crater when the water table is above the detonation point. Its effect is to flatten and widen the crater. The influence of a bedrock layer below a soil medium is similar to that of a water table, although somewhat less pronounced. For explosions at or near the surface, the bedrock layer has little effect on the crater radius, but may decrease the final depth considerably.

6.79 For relatively low-yield explosions at or very near the surface, the bedding or jointing planes in rock can alter significantly the shape of the crater and the direction of the ejection. The crater shape will tend to follow the direction of the predominant joints; the crater radius will increase in the direction parallel to the joints and decrease normal to the joints.

AIR BLAST PRESSURE

6.80 Several different mechanisms may operate to transfer part of the energy released in an underground explosion into the air and thereby produce air blast. For explosions at moderate depths, such that the fireball does not break through the surface, the predominant mechanisms may be described as follows. A shock wave propagated through the ground arrives at the surface and imparts an upward velocity to the air (air particles) at the air–ground interface, thus initiating an air pulse. At the same time, there may be spalling and upward motion of the surface layers, as explained in § 2.91. Meanwhile, the underground explosion gases expand, pushing the earth upward so that the spall merges into a dome at surface zero. The piston-like action of the spall and the rising dome increase the duration of the initial air pulse. The air blast sustained in this manner appears on pressure–time records as a single pulse, termed the air-transmitted, ground-shock-induced pulse. Somewhat later, the explosion gases puncture the dome and escape, creating a second air

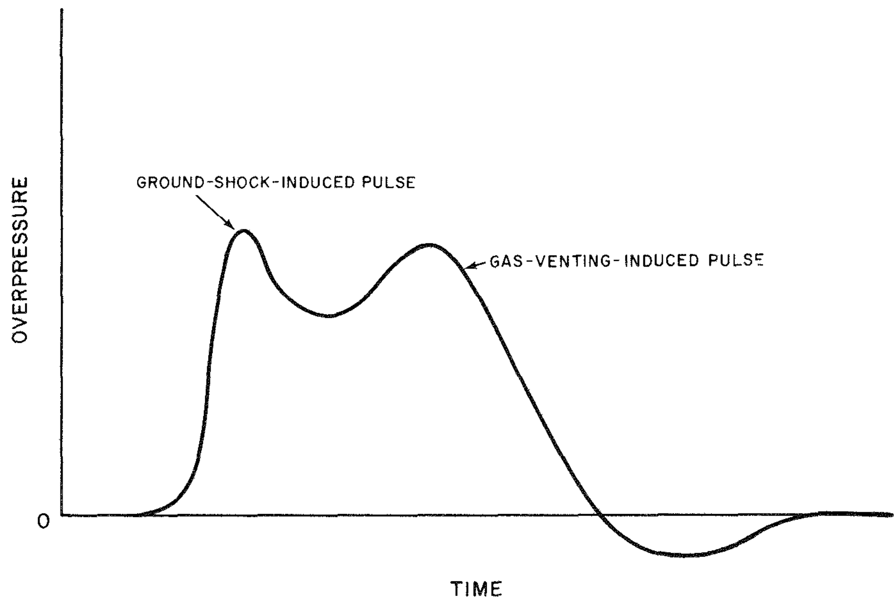

Figure 6.80. Air blast overpressure from underground explosions of moderate depth. With increasing burst depth, the relative contribution of gas venting decreases and the time between the pulses increases.

pulse called the gas-venting-induced pulse (Fig. 6.80).

6.81 With increasing depth of burst, the relative contribution of gas venting decreases and the time between the two pulses increases. Although the mechanisms that generate the air pulses change with depth in a complex manner, a procedure has been developed for predicting peak overpressures in the air near the surface as a function of distance from surface zero over a reasonable range of burial depths; the results are shown in Fig. 6.81. The value of $\bar{x}$ may be obtained from the following relations:

$$\bar{x} = \lambda_x e^{\rho\lambda_d/126},$$

$$\lambda_x = x/W^{1/3} \text{ and } \lambda_d = d/W^{1/3},$$

where x = ground distance in feet, d = depth of the explosion in feet, W = explosion yield in kilotons, and ρ = specific gravity of the ground medium. The curve in Fig. 6.81 may be used with the relations given above for scaled depths of burst, λ_d, less than 252 feet/KT$^{1/3}$. Typical values of specific gravities are 1.6 for alluvium, 1.9 for tuff, and 2.7 for granite.

GROUND MOTION

6.82 Earth shock motion at or near the surface accompanying a shallow or moderately deep underground burst may be regarded as consisting of systemic and random effects. The systemic effects are those associated with air blast and the shock wave transmitted directly

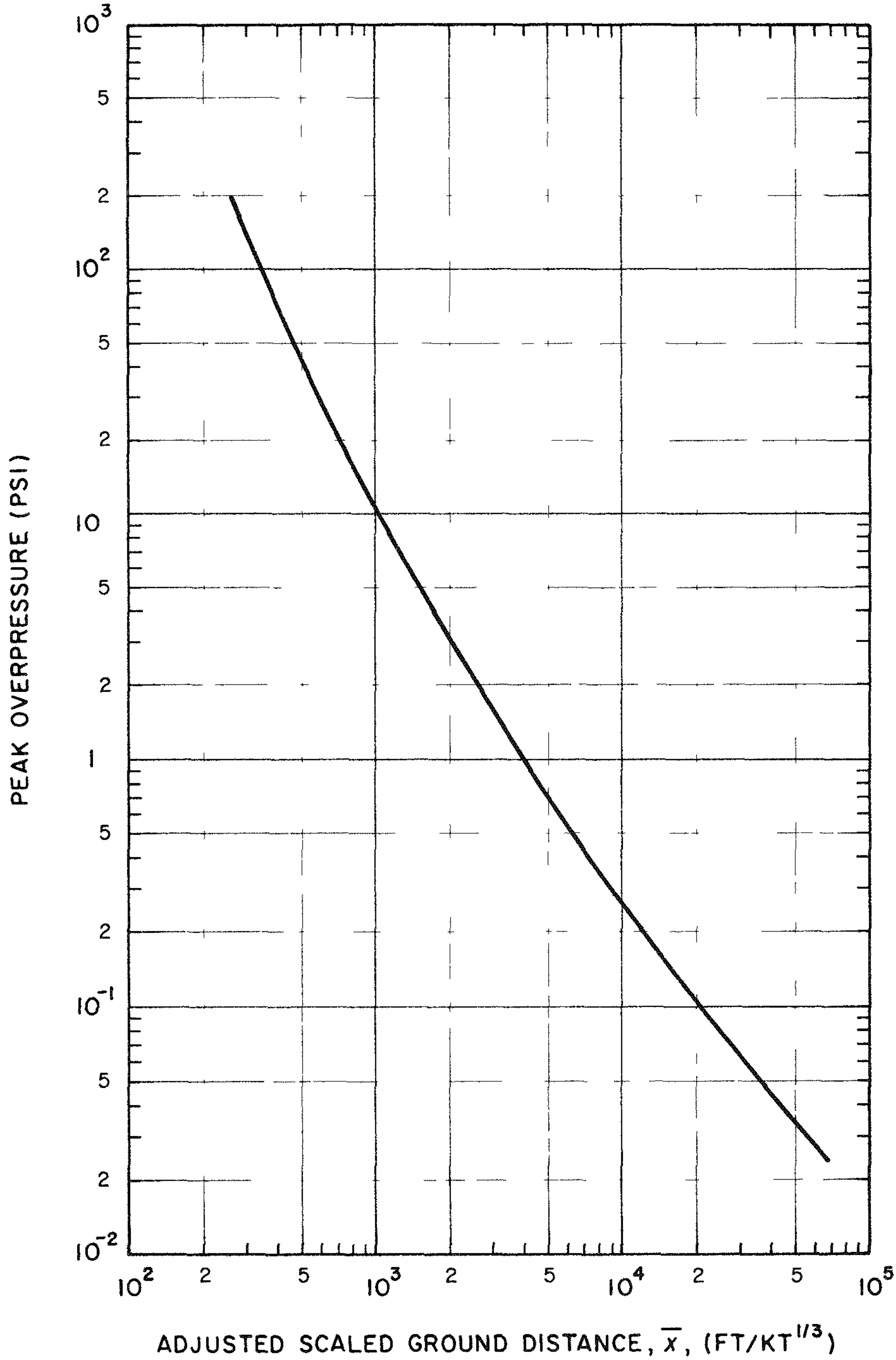

Figure 6 81 Peak overpressure of air blast from an underground explosion as a function of adjusted scaled ground distance from a buried 1-kiloton explosion

Table 6.108

DAMAGE CRITERIA FOR MODERATELY DEEP UNDERGROUND STRUCTURES

Structural Type	Damage Type	Distance from Surface Zero	Nature of Damage
Relatively small, heavy, well-designed, underground structures.	Severe	1¼ apparent crater radii	Collapse.
	Light	2½ apparent crater radii	Slight cracking, severance of brittle external connections.
Relatively long, flexible structures, e.g., buried pipelines, tanks, etc.	Severe	1½ apparent crater radii	Deformation and rupture.
	Moderate	2 apparent crater radii	Slight deformation and rupture.
	Light	2½ to 3 apparent crater radii	Failure of connections.

operative by the shock. Such equipment may be made less vulnerable by suitable shock mounting. Shock mounts (or shock isolators) are commonly made of an elastic material like rubber or they may consist of springs. The material absorbs much of the energy delivered very rapidly by the shock and releases it more slowly, thereby protecting the mounted equipment.

6.113 By shaking, vibrating, or dropping pieces of equipment, engineers can often estimate the vulnerability of that equipment to all kinds of motion. The results are commonly expressed as the natural vibration frequency at which the equipment is most vulnerable and the maximum acceleration tolerable at that frequency for 50 percent probability of severe damage. Some examples of the values of these parameters for four classes of equipment, without and with shock mounting, are quoted in Table 6.113. It is seen that the shock mounting serves to decrease the most sensitive natural fre-

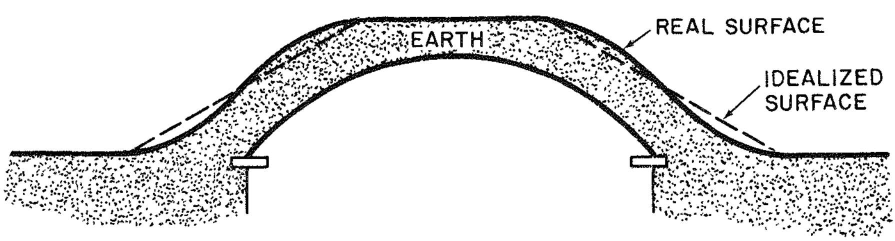

Figure 6.111. Configuration of mounded arch.

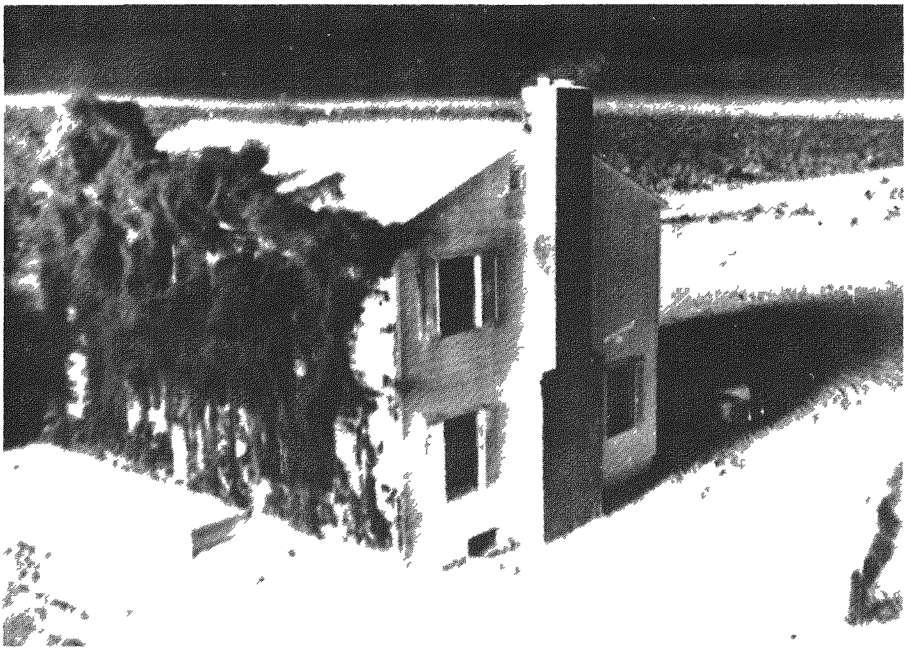

Figure 7 28a Thermal effects on wood-frame house 1 second after explosion (about 25 cal/cm²)

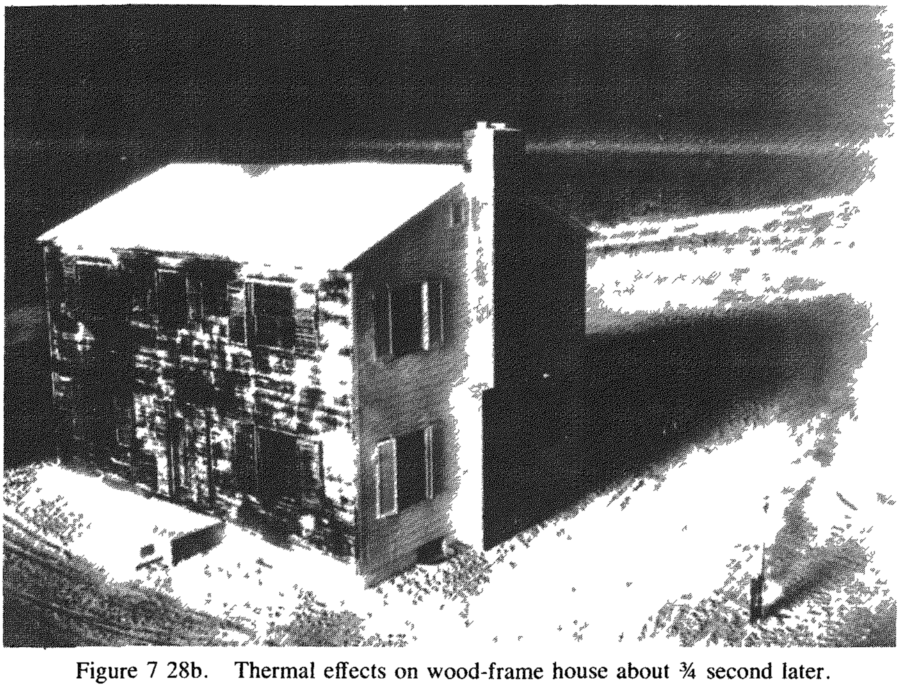

Figure 7 28b. Thermal effects on wood-frame house about ¾ second later.

Table 7.35

APPROXIMATE RADIANT EXPOSURES FOR IGNITION OF FABRICS FOR LOW AIR BURSTS

Material	Weight (oz/yd²)	Color	Effect on Material	Radiant Exposure* (cal/cm²) 35 kilotons	1.4 megatons	20 megatons
CLOTHING FABRICS						
Cotton	8	White	Ignites	32	48	85
		Khaki	Tears on flexing	17	27	34
		Khaki	Ignites	20	30	39
		Olive	Tears on flexing	9	14	21
		Olive	Ignites	14	19	21
		Dark blue	Tears on flexing	11	14	17
		Dark blue	Ignites	14	19	21
Cotton corduroy	8	Brown	Ignites	11	16	22
Cotton denim, new	10	Blue	Ignites	12	27	44
Cotton shirting	3	Khaki	Ignites	14	21	28
Cotton-nylon mixture	5	Olive	Tears on flexing	8	15	17
		Olive	Ignites	12	28	53
Wool	8	White	Tears on flexing	14	25	38
		Khaki	Tears on flexing	14	24	34
		Olive	Tears on flexing	9	13	19
		Dark blue	Tears on flexing	8	12	18
	20	Dark blue	Tears on flexing	14	20	26
Rainwear (double neoprene-coated nylon twill)	9	Olive	Begins to melt	5	9	13
		Olive	Tears on flexing	8	14	22
DRAPERY FABRICS						
Rayon gabardine	6	Black	Ignites	9	20	26
Rayon-acetate drapery	5	Wine	Ignites	9	22	28
Rayon gabardine	7	Gold	Ignites	**	24†	28†
Rayon twill lining	3	Black	Ignites	7	17	25
Rayon twill lining	3	Beige	Ignites	13	20	28
Acetate-shantung	3	Black	Ignites	10†	22†	35†
Cotton heavy draperies	13	Dark colors	Ignites	15	18	34
TENT FABRICS						
Canvas (cotton)	12	White	Ignites	13	28	51
Canvas	12	Olive drab	Ignites	12	18	28
OTHER FABRICS						
Cotton chenille bedspread		Light blue	Ignites	**	11†	15†
Cotton venetian blind tape, dirty		White	Ignites	10	18	22
Cotton venetian blind tape		White	Ignites	13†	27†	31†
Cotton muslin window shade	8	Green	Ignites	7	13	19

*Radiant exposures for the indicated responses (except where marked †) are estimated to be valid to ±25% under standard laboratory conditions. Under typical field conditions the values are estimated to be valid within ±50% with a greater likelihood of higher rather than lower values. For materials marked †, ignition levels are estimated to be valid within ±50% under laboratory conditions and within ±100% under field conditions.

**Data not available or appropriate scaling not known.

cal/cm^2, generally referred to as the "radiant exposure." Results are presented for low air bursts with arbitrary energy yields of 35 kilotons, 1.4 megatons, and 20 megatons. It will be noted that, for the reasons given in § 7.30, the radiant exposure required to produce a particular effect increases with the yield.

7.36 Since the shape and duration of the thermal pulse depend on the actual burst altitude, as well as on the yield, the radiant exposures given in Table 7.35 for "low air bursts" are somewhat approximate. In general, however, the radiant exposures in the three columns would apply to nuclear explosions below 100,000 feet altitude for which the times to the second maximum in the fireball temperature are 0.2, 1.0, and 3.2 seconds, respectively (§ 7.85).

7.37 Wood is charred by exposure to thermal radiation, the depth of the char being closely proportional to the radiant exposure. For sufficiently large amounts of energy per unit area, wood in some massive forms may exhibit transient flaming but persistent ignition is improbable under the conditions of a nuclear explosion. However, the transitory flame may ignite adjacent combustible material which is not directly exposed to the radiation. In a more-or-less finely divided form, such as sawdust, shavings, or excelsior, or in a decayed, spongy (punk) state, wood can be ignited fairly readily by the thermal radiation from a nuclear explosion, as will be seen below.

7.38 Roughly speaking, something like 10 to 15 calories per square centimeter of thermal energy are required to produce visible charring of unpainted and unstained pine, douglas fir, redwood, and maple. Dark staining increases the tendency of the wood to char, but light-colored paints and hard varnishes provide protection.[2]

7.39 Glass is highly resistant to heat, but as it is very brittle it is sometimes replaced by transparent or translucent plastic materials or combined with layers of plastic, as in automobile windshields, to make it shatterproof. These plastics are organic compounds and so are subject to decomposition by heat. Nevertheless, many plastic materials, such as Bakelite, cellulose acetate, Lucite, Plexiglas, polyethylene, and Teflon, have been found to withstand thermal radiation remarkably well. At least 60 to 70 cal/cm^2 of thermal energy are required to produce surface melting or darkening.

RADIANT EXPOSURES FOR IGNITION OF VARIOUS MATERIALS

7.40 Studies have been made in laboratories and at nuclear tests of the radiant exposures required for the ignition of various common household items and other materials of interest. The results for low air bursts with three arbitrary yields are presented in Table 7.40; the conditions and limitations noted in § 7.36 also hold here. The radiant exposures given would be applicable to explosions at altitudes below 100,000 feet.

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[2] The thermal radiation energy incident on the front of the house referred to in § 7.28 was about 25 cal/cm^2.

Table 7.40

APPROXIMATE RADIANT EXPOSURES FOR IGNITION OF VARIOUS MATERIALS FOR LOW AIR BURSTS

Material	Weight (oz/yd^2)	Color	Effect on Material	Radiant Exposure* (cal/cm^2) 35 kilotons	1 4 megatons	20 megatons
HOUSEHOLD TINDER MATERIALS						
Newspaper, shredded	2		Ignites	4	6	11
Newspaper, dark picture area	2		Ignites	5	7	12
Newspaper, printed text area	2		Ignites	6	8	15
Crepe paper	1	Green	Ignites	6	9	16
Kraft paper	3	Tan	Ignites	10	13	20
Bristol board, 3 ply	10	Dark	Ignites	16	20	40
Kraft paper carton, used (flat side)	16	Brown	Ignites	16	20	40
New bond typing paper	2	White	Ignites	24†	30†	50†
Cotton rags		Black	Ignites	10	15	20
Rayon rags		Black	Ignites	9	14	21
Cotton string scrubbing mop (used)		Gray	Ignites	10†	15†	21†
Cotton string scrubbing mop (weathered)		Cream	Ignites	10†	19†	26†
Paper book matches, blue head exposed			Ignites	11†	14†	20†
Excelsior, ponderosa pine	2 lb/ft^3	Light yellow	Ignites	**	23†	23†
OUTDOOR TINDER MATERIALS***						
Dry rotted wood punk (fir)			Ignites	4†	6†	8†
Deciduous leaves (beech)			Ignites	4	6	8
Fine grass (cheat)			Ignites	5	8	10
Coarse grass (sedge)			Ignites	6	9	11
Pine needles, brown (ponderosa)			Ignites	10	16	21
CONSTRUCTION MATERIALS						
Roll roofing, mineral surface			Ignites	**	>34	>116
Roll roofing, smooth surface			Ignites	**	30	77
Plywood, douglas fir			Flaming during exposure	9	16	20
Rubber, pale latex			Ignites	50	80	110
Rubber, black			Ignites	10	20	25
OTHER MATERIALS						
Aluminum aircraft skin (0 020 in thick) coated with 0 002 in of standard white aircraft paint			Blisters	15	30	40
Cotton canvas sandbags, dry filled			Failure	10	18	32
Coral sand			Explodes (popcorning)	15	27	47
Siliceous sand			Explodes (popcorning)	11	19	35

*Radiant exposures for the indicated responses (except where marked †) are estimated to be valid to ±25% under standard laboratory conditions Under typical field conditions, the values are estimated to be valid within ±50% with a greater likelihood of higher rather than lower values For materials marked †, ignition levels are estimated to be valid within ±50% under laboratory conditions and within ±100% under field conditions

**Data not available or appropriate scaling not known

***Radiant exposures for ignition of these substances are highly dependent on the moisture content

RADIANT EXPOSURE AND SLANT RANGE

7.41 In order to utilize the data in Tables 7.35 and 7.40 to determine how far from the burst point, for an explosion of given energy yield, ignition of a particular material would be observed, it is required to know how the thermal energy varies with distance. For a specific explosion yield, the variation of radiation exposure with distance from the point of burst depends upon a number of factors, including the height of burst and the condition (or clarity) of the atmosphere. As seen earlier, the proportion of the total yield that appears as thermal energy and the character and duration of the thermal pulse vary with the height of burst. Furthermore, the height of burst and the atmospheric visibility determine the fraction of the thermal energy that can penetrate the atmosphere.

7.42 The variation of radiant exposure on the ground with slant range from the explosion for a particular set of conditions can be conveniently represented in the form of Fig. 7.42. These curves were calculated for burst heights of 200 $W^{0.4}$ feet, where W is the explosion yield in kilotons (see § 7.99), but they provide reasonably good predictions of radiant exposures from air bursts at altitudes up to about 15,000 feet, for a visibility of 12 miles. This visibility represents the conditions for typical urban areas on a clear day. For air bursts at altitudes above 15,000 feet, Fig. 7.42 is not satisfactory and the procedures described in § 7.93 *et seq.* should be used. For bursts at low altitudes, e.g., less than 180 $W^{0.4}$ feet, which are essentially surface bursts (cf. § 2.128), radiant exposures should be calculated by using the procedures in § 7.101 *et seq.*

7.43 The application of Fig. 7.42 may be illustrated by estimating the range over which ignition may occur in newspaper as a result of exposure to a 1000-kiloton (1-megaton) air burst under the conditions specified above. According to Table 7.40, the radiant exposure for the ignition of newspaper is about 8 cal/cm^2 in a 1-megaton explosion. Fig. 7.42 is entered at the point on the yield scale corresponding to 1 megaton (10^3 kilotons); the perpendicular line is then followed until it intersects the curve marked 8 cal/cm^2 of radiant exposure. The intersection is seen to correspond to a slant range of about 7 miles from the explosion. This is the range at which the thermal radiation from a 1-megaton air burst (below 15,000 feet altitude) could cause ignition in newspaper when the visibility is 12 miles. Under hazy conditions, such as often exist in large cities, the visibility would be less and the ignition range might be smaller. Similarly, a layer of dense cloud or smoke between the target and the burst point will decrease the distance over which a specified ignition may occur. However, if the explosion were to take place between a cloud layer and the target or if the ground surface is highly reflective, as when covered with snow, the distance would be greater than indicated by Fig. 7.42.

THERMAL EFFECTS ON MATERIALS IN JAPAN[3]

7.44 Apart from the actual ignition of combustible materials resulting in

[3]The effects of thermal radiations on people in Japan are described in Chapter XII.

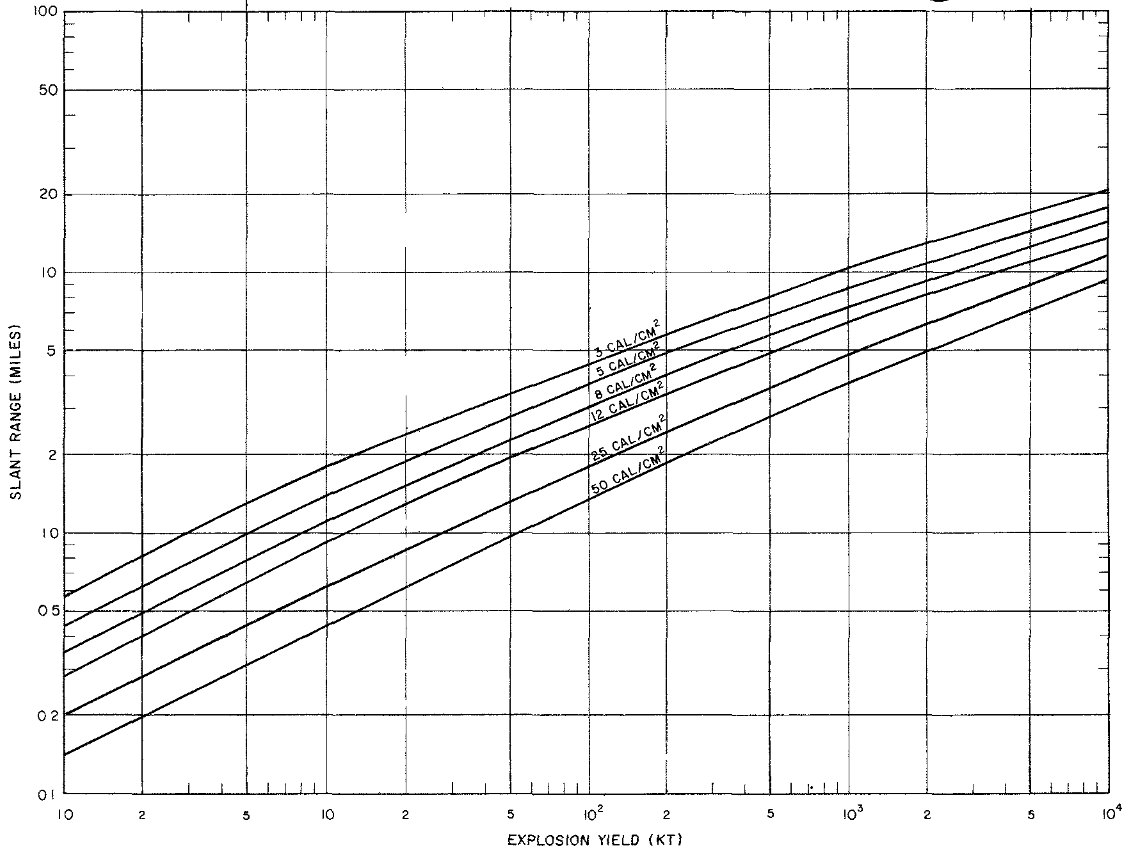

Figure 7.42. Slant ranges for specified radiant exposures on the ground as a function of energy yield of air bursts at altitudes up to 15,000 feet for a 12-mile visibility

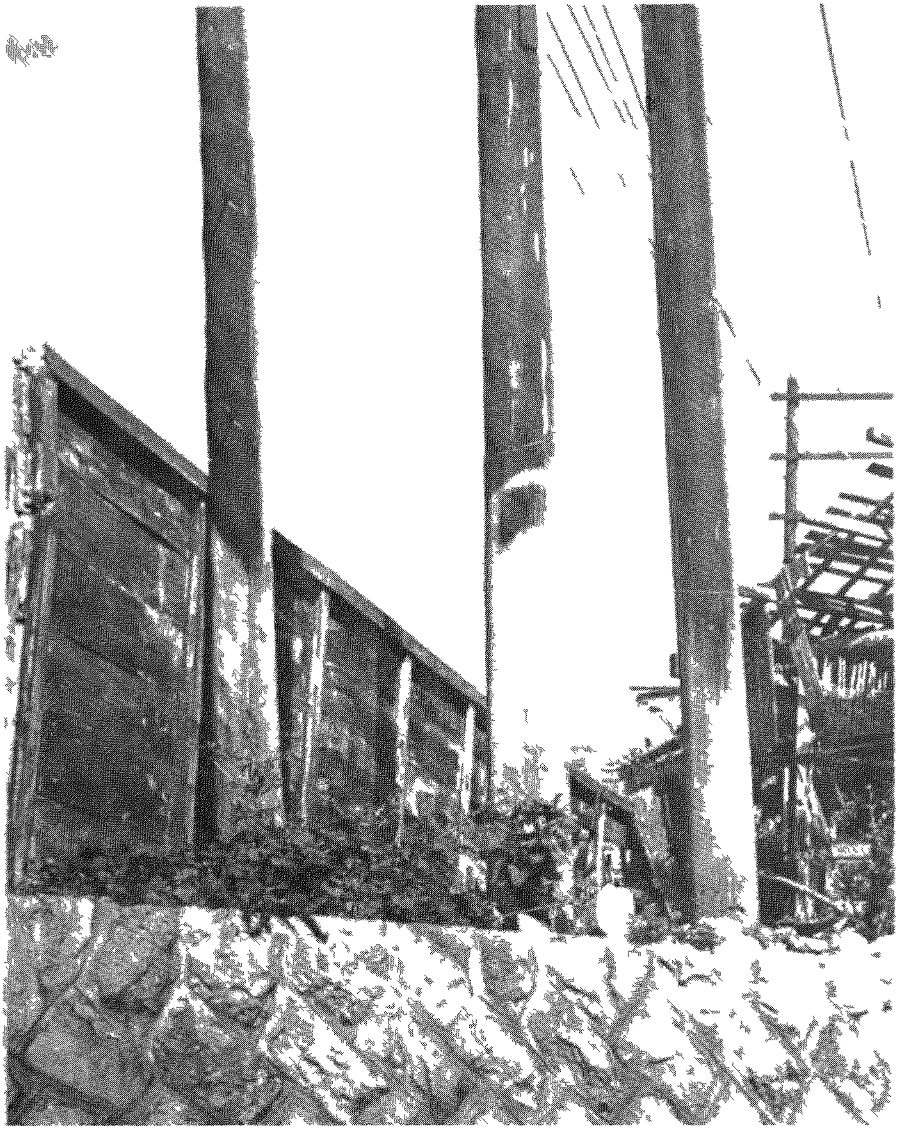

Figure 7 44b Flash burns on wooden poles (1 17 miles from ground zero at Nagasaki, 5 to 6 cal/cm²) The uncharred portions were protected from thermal radiation by a fence etc , are concerned. However, the early-time debris, which separates from the X-ray pancake (§ 2.135), is at a fairly high temperature and it emits a very short pulse of thermal energy that can cause eye injury to individuals looking directly at the explosion (§ 12.79 *et seq.*)

RADIANT EXPOSURE–DISTANCE RELATIONSHIPS

AIR BURSTS

7.93 The following procedure is used to calculate the dependence of the radiant exposure of a target (§ 7 35) upon its distance from an air burst of specified yield. As seen earlier in this chapter, such information, which is given in Fig 7.42, combined with the data in Tables 7.35 and 7.40, permits estimates to be made of the probable ranges for various thermal radiation effects.

7.94 If there is no atmospheric attenuation, then at a distance D from the explosion the thermal radiation energy, E_{tot} may be regarded as being spread uniformly over the surface of a sphere of area $4\pi D^2$ If the radiating fireball is treated as a point source, the energy received per unit area of the sphere would be $E_{tot}/4\pi D^2$. If attenuation were due only to absorption in a uniform atmosphere, e.g., for an air burst, this quantity would be multiplied by the factor $e^{-\kappa D}$, where κ is an absorption coefficient averaged over the whole spectrum of wavelengths. Hence in these circumstances, using the symbol Q to represent the radiant exposure, i.e., the energy received per unit area normal to the direction of propagation, at a distance D from the explosion, it follows that

$$Q = \frac{E_{tot}}{4\pi D^2} e^{-\kappa D} \qquad (7.94.1)$$

7.95 When scattering of the radiation occurs, in addition to absorption, the coefficient κ changes with distance and other variables. The simple exponential attenuation factor in equation (7.94.1) is then no longer adequate A more useful (empirical) formulation is

$$Q = \frac{E_{tot}\tau}{4\pi D^2}, \qquad (7.95.1)$$

where the transmittance, τ, i e., the fraction of the radiation (direct and scattered) which is transmitted, is a complex function of the visibility (scattering), absorption, and distance.[5]

7.96 Since $E_{tot} = fW$, equation (7 95.1) for the radiant exposure from an air burst of yield W can be expressed as

$$Q = \frac{fW\tau}{4\pi D^2}. \qquad (7\ 96.1)$$

---

[5] Scattered radiation does not cause permanent damage to the retina of the eye Hence, to determine the effective radiant exposure in this connection equation (7 94 1) should be used, κ is about 0 03 km^{-1} for a visibility of 80 km (50 miles), 0 1 km^{-1} for 40 km (25 miles) and 0 2 km^{-1} for 20 km (12 4 miles) Scattered radiation can, however, contribute to flashblindness, resulting from the dazzling effect of bright light (§ 12 83)

By utilizing the fact that 1 kiloton of TNT is equivalent to 10^{12} calories, equation (7.96.1) for an air burst becomes

$$Q\ (\text{cal/cm}^2) = \frac{10^{12} f W \tau}{4\pi D^2} \qquad (7.96.2)$$

where D is in centimeters and W is in kilotons. If the distance, D, from the explosion to the target, i.e., the slant range, is expressed in kilofeet or miles, equation (7.96.2) reduces approximately to

$$D \text{ in kilofeet} \quad Q\ (\text{cal/cm}^2) \approx \frac{85.6\, f W \tau}{D^2} \qquad (7.96.3)$$

$$D \text{ in miles} \quad Q\ (\text{cal/cm}^2) \approx \frac{3.07\, f W \tau}{D^2} \qquad (7.96.4)$$

7.97 In nuclear weapons tests, it is possible to measure Q and W, and since the distance D from the explosion is known the magnitude of the product $f\tau$ can be determined from the equations in § 7.96. Hence, to obtain f and τ individually, one of these two quantities must be determined independently of the other. The method used is to obtain f for different conditions from calculations checked by observations, as stated in § 7.88. The values of τ are then derived from measurements of $f\tau$ made at a large number of weapons tests.

7.98 The transmittance τ for any given atmospheric condition depends on the solid angle over which scattered radiation can reach a particular exposed object. For the present purpose it will be assumed that the target is such, e.g., an appreciable flat area, that scattered radiation is received from all directions above, in addition to the direct thermal radiation from the source. Transmittance data for these conditions are presented in Fig. 7.98 in terms of burst altitude and distance of a surface target from ground zero for a cloudless atmosphere with a visibility of 12 miles. Since actual visibilities in cities are often less, the values in Fig. 7.98 are conservative.

7.99 The transmittance values in Fig. 7.98 were used, in conjunction with equation (7.96.4) and the thermal partitions from Table 7.88, to obtain the data from which the curves in Fig. 7.42 were constructed. If H is the height of burst and d is the distance from ground zero of a given point on the surface, the corresponding slant range for use in equation (7.96.4) is $D = (d^2 + H^2)^{1/2}$. A height of burst of 200 $W^{0.4}$ feet, with W in kilotons, was used for the calculations, but the results in Fig. 7.42 are reasonably accurate for air bursts at any altitude up to some 15,000 feet.

7.100 Under unusual conditions and especially for cities at high-altitude locations, the visibility might be greater than at sea level and the transmittance would be larger than the values given in Fig. 7.98. The curves show that most attenuation of radiation occurs within a few thousand feet of the surface; thus, the much clearer air at higher altitudes has less effect. For bursts above about 150,000 feet (28 miles), the transmittance changes slowly with the altitude. Experimental data indicate that multiplying the transmittance by 1.5 corrects approximately for the effect of reflection from a cloud layer over the burst. The same correction may be made for a snow-covered ground surface. If the burst and target are both between a

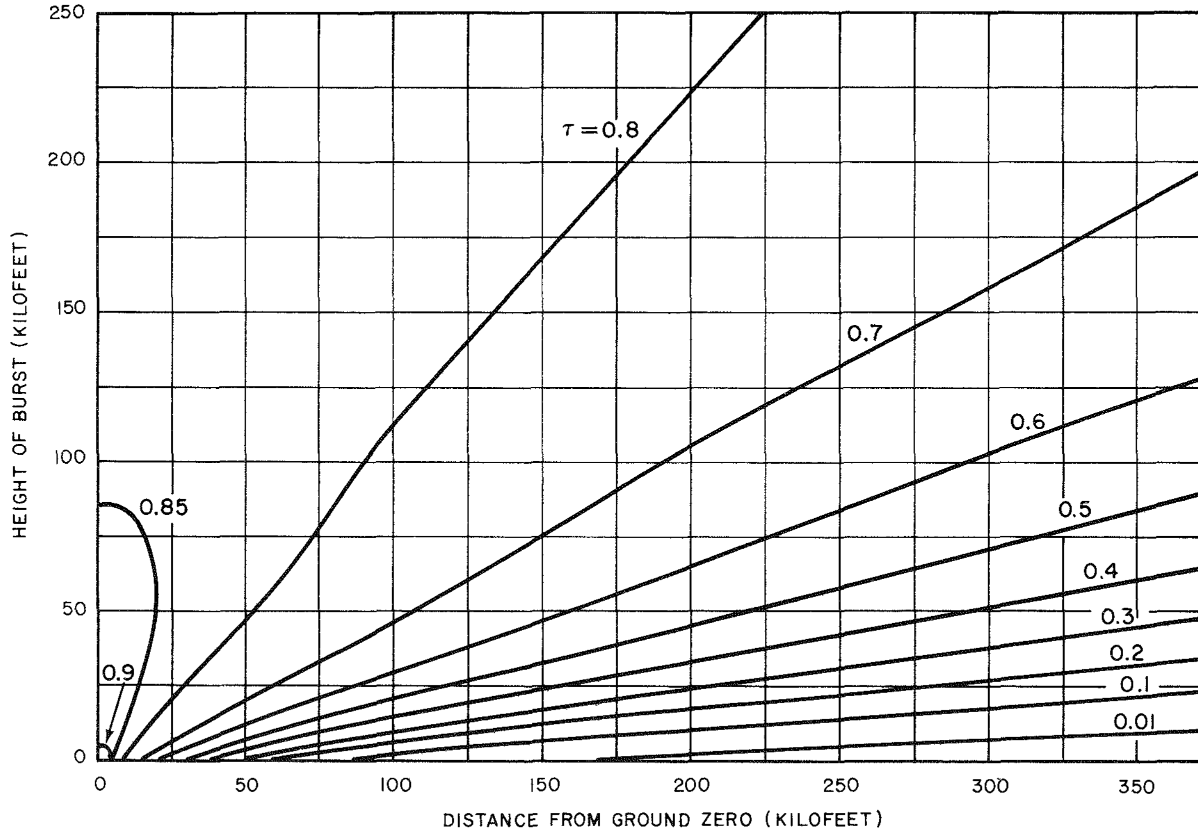

Figure 7.98. Transmittance, τ, to a target on the ground on a typical clear day (visibility = 12 miles).

cloud layer and a snow covered surface, the correction is 1.5 × 1.5 = 2.25.

SURFACE BURSTS

7.101 For a surface burst, the radiant exposures along the earth's surface will be less than for equal distances from an air burst of the same total yield. This difference arises partly, as indicated in § 7.20, from the decreased transmittance of the intervening low air layer due to dust and water vapor produced by the explosion. Furthermore, the normal atmosphere close to the earth's surface transmits less than at higher altitudes. In order to utilize the equations in § 7.96 to determine radiant exposure for surface bursts, the concept of an "effective thermal partition" is used, together with the normal transmittance, such as given in Fig. 7.98, for the existing atmospheric conditions. Based upon experimental data, contact surface bursts can be represented fairly well by an effective thermal partition of 0.18. Values of the thermal partition for other surface bursts are shown in Table 7.101; they have been derived by assigning a thermal partition of 0.18 to a contact surface burst and interpolating between that value and the air burst thermal partition values in Table 7.88.

VERY-HIGH-ALTITUDE BURSTS

7.102 In the calculation of the thermal radiation exposure at the surface of the earth from very-high-altitude nuclear explosions, two altitude regions must be considered because of the change in the fireball behavior that occurs at altitudes in the vicinity of about 270,000 feet (§ 7.91). At burst heights from roughly 160,000 to 200,000 feet (30 to 38 miles), the ther-

Table 7.101

EFFECTIVE THERMAL PARTITION FOR SURFACE BURSTS

Height of Burst (feet)	Thermal Partition: Total Yield (kilotons) 1	10	100	1,000	10,000
20	0.19	*	*	*	*
40	0.21	0.19	*	*	*
70	0.23	0.21	0.19	*	*
100	0.26	0.22	0.20	*	*
200	0.35	0.25	0.21	0.19	*
400	**	0.33	0.25	0.21	0.19
700	**	**	0.28	0.24	0.21
1,000	**	**	0.34	0.26	0.22
2,000	**	**	**	0.34	0.26
4,000	**	**	**	**	0.33
7,000	**	**	**	**	0.35

*These may be treated as contact surface bursts, with $f = 0.18$.
**Air bursts; for values of f see Table 7.88.

mal energy capable of causing damage at the surface of the earth drops sharply from about 60 percent to about 25 percent, i.e., from $f = 0.60$ to $f = 0.25$. As the height of burst is increased above 200,000 feet, the thermal partition remains about 0.25 up to a height of burst of approximately 260,000 feet (49 miles). Since a nearly spherical fireball forms within this latter altitude region, equation (7.93.3) becomes

$$Q \text{ (cal/cm}^2) = \frac{21.4\ W_T}{D^2}, \quad (7.102.1)$$

where D is the slant range in kilofeet, and W is the yield in kilotons. A linear interpolation of the variation of thermal partition with burst altitude may be performed for bursts between 160,000 feet and 200,000 feet; however, in view of the uncertainties in high-altitude burst phenomenology, it may be desirable to use the high (0.60) or the low (0.25) value throughout this burst altitude region, depending on the degree of conservatism desired.

7.103 At burst altitudes of roughly 270,000 feet and above, the thermal radiation is emitted from the thick X-ray pancake at a mean altitude of about 270,000 feet, essentially independent of the actual height of burst (§ 7.91). In order to use the equations in § 7.96 to calculate radiant exposures at various distances from the burst, the approximation is made of replacing the disklike radiating region by an equivalent source point defined in the following manner. If the distance d from ground zero to the target position where Q is to be calculated is less than the height of burst, H, the source may be regarded as being located at the closest point on a circle with the median radius at an altitude of 270,000 feet; this is indicated by the point S in Fig. 7.103. Hence, for the target point X, the appropriate slant range is given approximately by

$$D \text{ (kilofeet)} \approx \{(270)^2 + [\tfrac{1}{2}(H - 270) - d]^2\}^{1/2}, \quad (7.103.1)$$

with d and H in kilofeet. This expression holds even when d is greater than $\tfrac{1}{2}(H - 270)$; although the quantity in the square brackets is then negative, the square is positive. The slant range, D_0, for ground zero is obtained by setting d in equation (7.103.1) equal to zero; thus,

$$D_0 \text{ (kilofeet)} \approx [(270)^2 + \tfrac{1}{2}(H - 270)^2]^{1/2}.$$

If the distance d is greater than the height of burst, the equivalent point source may be taken to be approximately at the center of the radiating disk at 270,00 feet altitude; then

$$D \text{ (kilofeet)} \approx [(270)^2 + d^2]^{1/2}.$$

7.104 For the heights of burst under consideration, it is assumed that the fraction 0.8 of the total yield is emitted as X-ray energy and that 0.25 of this energy is absorbed in the radiating disk region. Hence, $0.8 \times 0.25 = 0.2$ of the total yield is absorbed. For calculating the radiant exposure, the total yield W in the equations in § 7.96 is consequently replaced by $0.2W$. Furthermore, the equivalent of the thermal partition is called the "thermal efficiency," ε, defined as the effective fraction of the absorbed energy that is

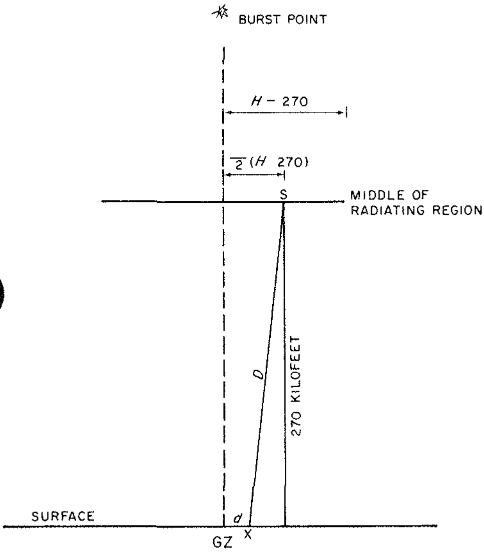

Figure 7.103 Equivalent point source at median radius when height of burst exceeds distance of the target X from ground zero.

reradiated. Hence equation (7.96.3), for example, becomes

$$Q \text{ (cal/cm}^2) = \frac{17.1\ \varepsilon\ W_T}{D^2},$$

where D in kilofeet is determined in accordance with the conditions described in the preceding paragraph. The values of ε given in Fig. 7.104 as a function of height of burst and yield were obtained by theoretical calculations.[6] The transmittance may be estimated from Fig. 7.98 but no serious error would be involved by setting it equal to unity for the large burst heights involved.

7.105 With the information given above, it is possible to utilize the equations in § 7.96 to calculate the approximate radiant exposure, Q, for points on the earth's surface at a given distance, d, from ground zero, for a prescribed height of burst, H, for explosions of essentially all burst altitudes. If d and H are specified, the appropriate slant range can be determined. Tables 7.88 and 7.101 and Fig. 7.104 are used to obtain the required thermal partition or thermal efficiency, and the transmittance can be estimated from Fig. 7.98 for the known d and H. Suppose, however, it is required to reverse the calculations and to find the slant range to a surface target (or the corresponding distance from ground zero for a specified height of burst) at which a particular value of Q will be attained. The situation is then much more difficult because τ can be estimated only when the slant range or distance from ground zero is known. One approach would be to prepare figures like Fig. 7.42 for several heights of burst and to interpolate among them for any other burst height. Another possibility is to make use of an interation procedure by guessing a value of τ, e.g., $\tau = 1$, to determine a first approximation to D. With this value of D and the known height of burst, an improved estimate of τ can be obtained from Fig. 7.98. This is then utilized to derive a better approximation to D, and so on until convergence is attained.

[6] The calculations are actually for the fraction of the absorbed X ray energy reradiated within 10 seconds; for estimating effects on the ground the subsequent reradiation can be neglected.

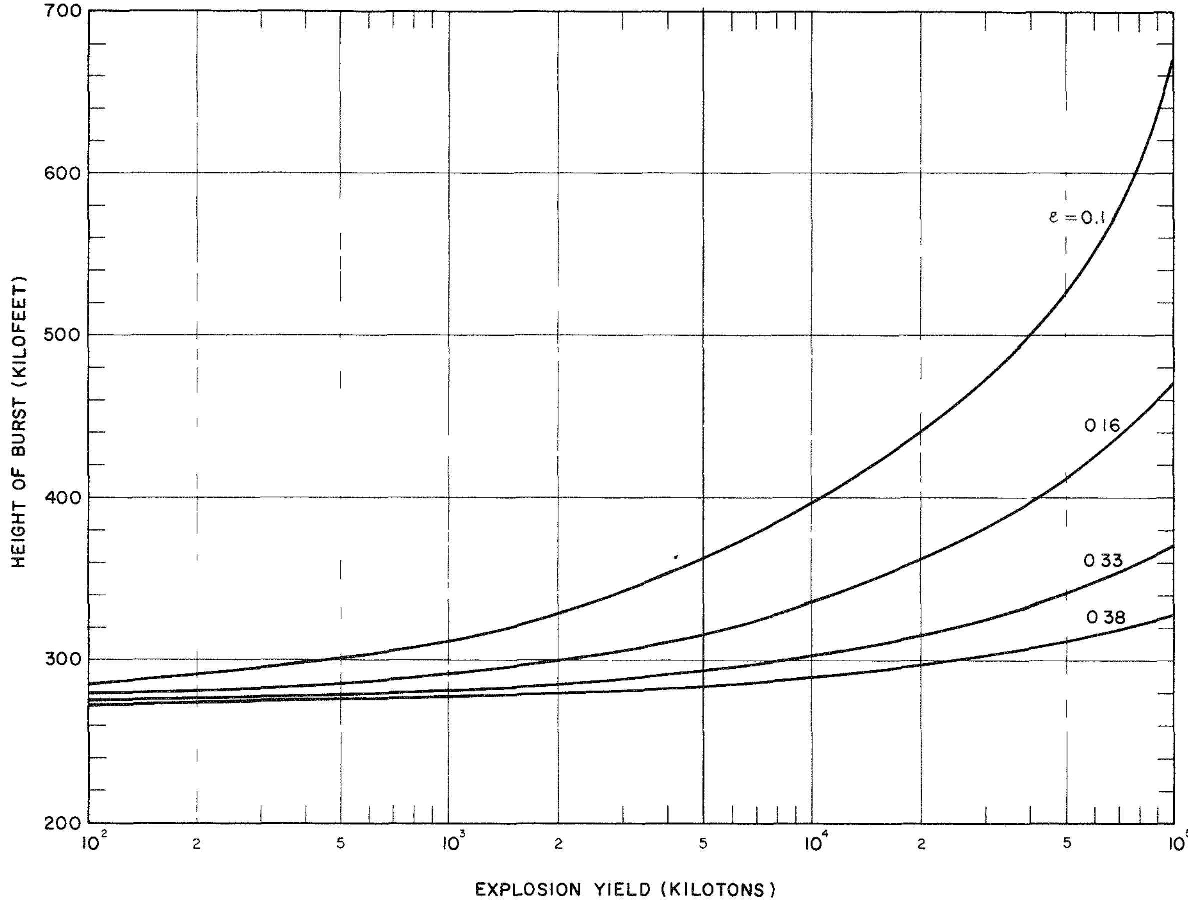

Figure 7.104. Fraction of absorbed X-ray energy reradiated from high-altitude bursts.

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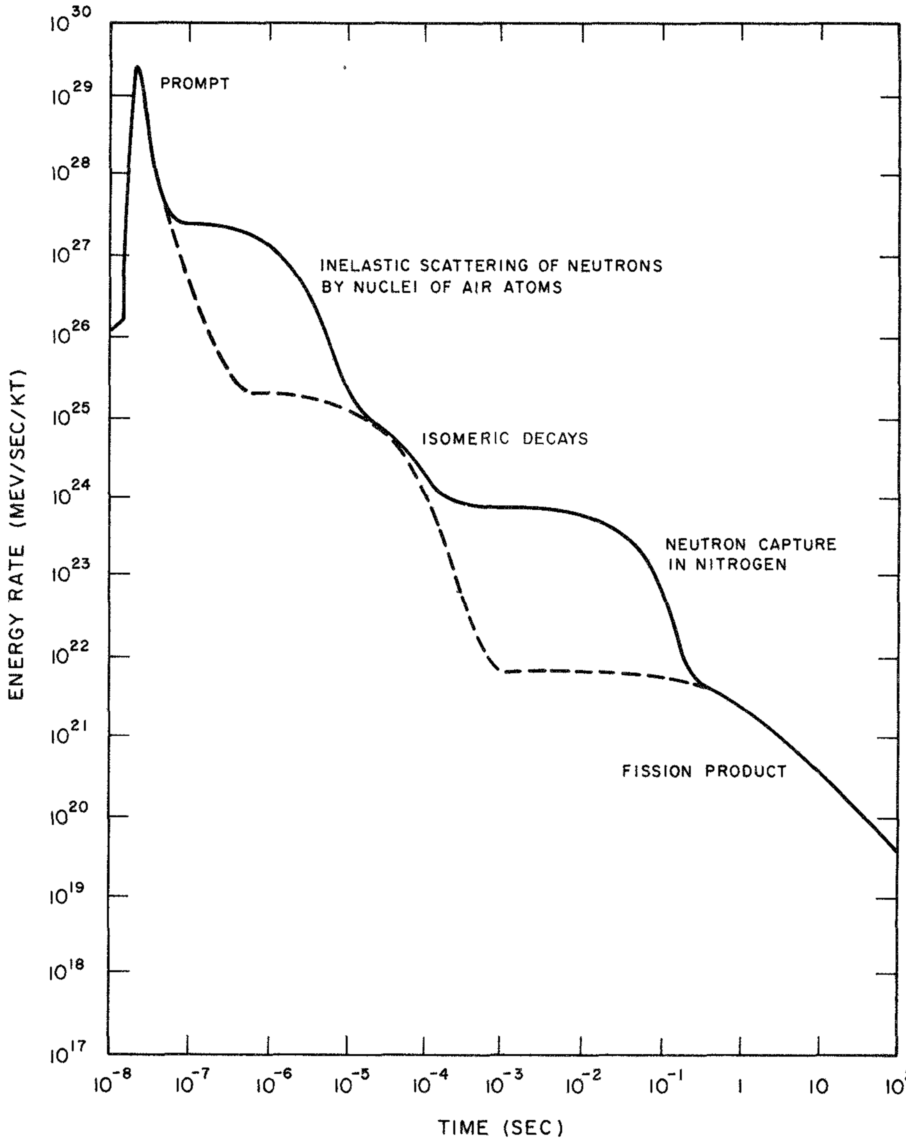

Figure 8.14. Calculated time dependence of the gamma-ray energy output per kiloton energy yield from a hypothetical nuclear explosion. The dashed line refers to an explosion at very high altitude.

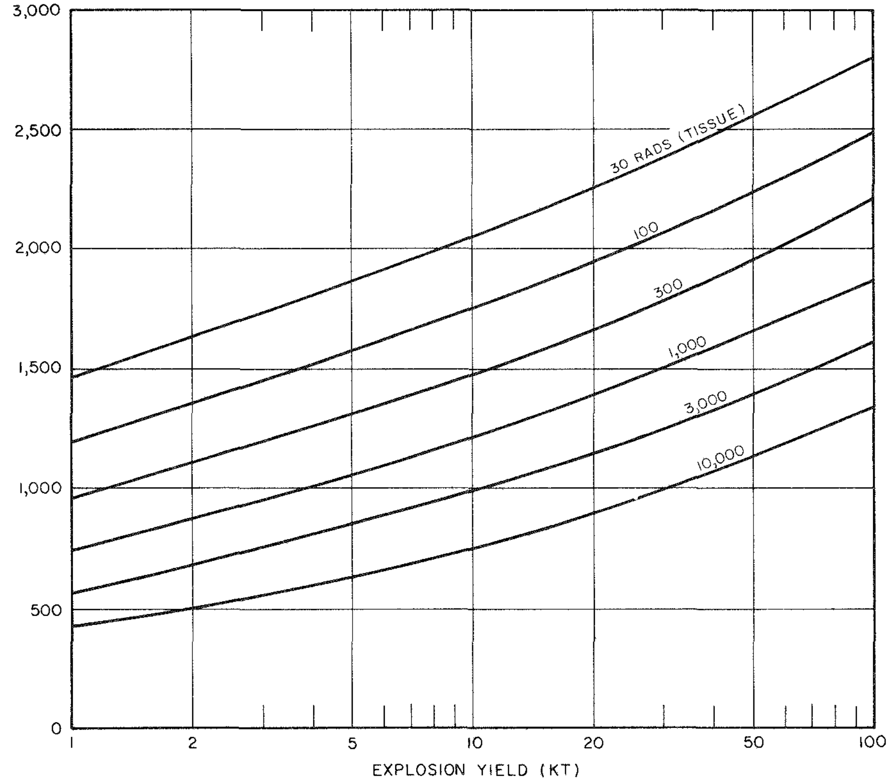

Figure 8.33a. Slant ranges for specified gamma-ray doses for targets near the ground as a function of energy yield of air-burst fission weapons, based on 0.9 sea-level air density. (Reliability factor from 0.5 to 2 for most fission weapons.)

the explosion center. As with thermal radiation (§ 7.07), the dose received is inversely proportional to the square of the distance from the burst point, so that it is said to be governed by the "inverse square" law. Second, there is an attenuation factor to allow for the decrease in intensity due to absorption and scattering of gamma rays by the intervening atmosphere.

8.33 The gamma-radiation doses at known distances from explosions of different energy yields have been measured at a number of nuclear weapons tests. Extensive computer calculations have also been performed of the transport of gamma rays through the air. These calculations have been correlated with measurements of the gamma-ray transport from known sources and with observations made at nuclear explosions. The results obtained for air bursts are summarized in the form of two graphs: the first (Fig. 8.33a) shows the relation between yield and slant range for various absorbed gamma-ray doses (in tissue near the body surface, see § 8.18) for fission weapons; the second (Fig. 8.33b) gives similar information for thermonuclear weapons with 50

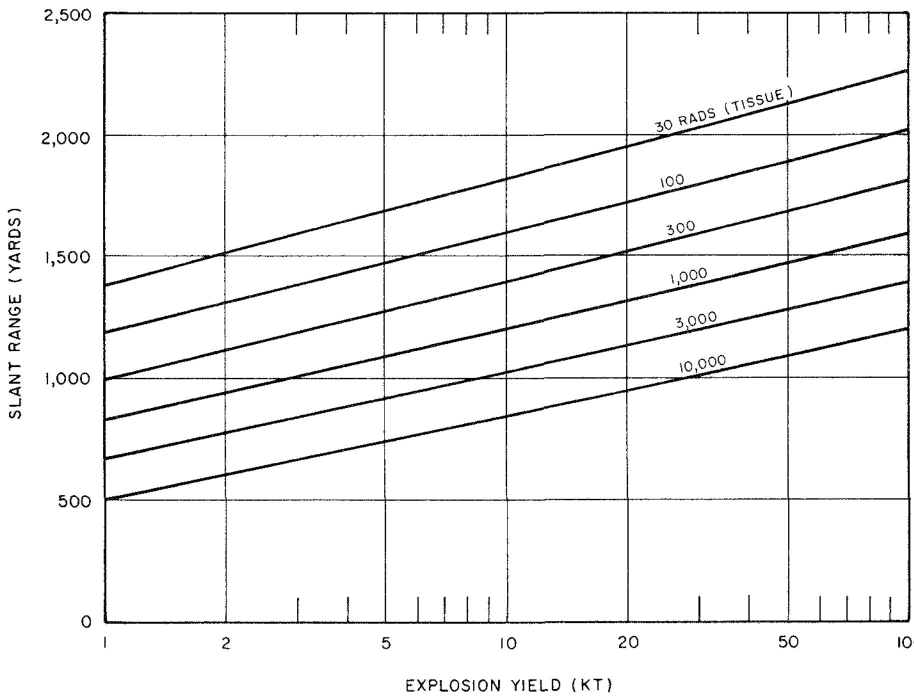

Figure 8 64a Slant ranges for specified neutron doses for targets near the ground as a function of energy yield of air-burst fission weapons, based on 0 9 sea-level air density (Reliability factor from 0 5 to 2 for most fission weapons)

contact surface bursts, the prompt neutron dose may be taken as one-half the value for a corresponding air burst. For heights of burst below 300 feet, the dose may be estimated by interpolation between the values for an air burst and a contact surface burst.

SHIELDING AGAINST NEUTRONS

8.66 Neutron shielding is a different, and more difficult, problem than shielding against gamma rays. As far as the latter are concerned, it is merely a matter of interposing a sufficient mass of material between the source of gamma radiations and the recipient. Heavy metals, such as iron and lead, make good gamma-ray shields because of their high density. These elements alone, however, are not quite as satisfactory for neutron shielding. An iron shield will attenuate weapon neutrons to some extent, but it is less effective than some of the types described below.

8.67 The attenuation of neutrons from a nuclear explosion involves several different phenomena. First, the very fast neutrons must be slowed down into the moderately fast range; this requires a suitable (inelastic) scattering material, such as one containing barium or iron. Then, the moderately fast neutrons have to be decelerated (by elastic scattering) into the slow range by means of an element of low atomic weight (or mass

Table 8.72

DOSE TRANSMISSION FACTORS FOR VARIOUS STRUCTURES

Structure	Initial Gamma Rays	Neutrons
Three feet underground	0.002–0.004	0.002–0.01
Frame House	0.8–1.0	0.3–0.8
Basement	0.1–0.6	0.1–0.8
Multistory building (apartment type):		
Upper stories	0.8–0.9	0.9–1.0
Lower stories	0.3–0.6	0.3–0.8
Concrete blockhouse shelter:		
9-in. walls	0.1–0.2	0.3–0.5
12-in. walls	0.05–0.1	0.2–0.4
24-in. walls	0.007–0.02	0.1–0.2
Shelter, partly above grade:		
With 2 ft earth cover	0.03–0.07	0.02–0.08
With 3 ft earth cover	0.007–0.02	0.01–0.05

TRANSIENT-RADIATION EFFECTS ON ELECTRONICS (TREE)

GENERAL CHARACTERISTICS OF TREE

8.73 The initial nuclear radiation, specifically gamma rays and neutrons, can affect materials, such as those used in electronics systems, e.g., radio and radar sets, gyroscopes, inertial guidance devices, computers, etc. The response of such systems to radiation from a nuclear explosion depends on the nature of the radiation absorbed and also on the specific component and often on the operating state of the system. The actual effects are determined by the characteristics of the circuits contained in the electronics package, the exact components present in the circuits, and the specific construction techniques and materials used in making the components.

8.74 The name commonly applied to the class of effects under consideration is "transient-radiation effects on electronics," commonly abbreviated to the acronym TREE. In general, TREE means those effects occurring in an electronics system as a result of exposure to the transient initial radiation from a nuclear weapon explosion. The adjective "transient" applies to the radiation since it persists for a short time, i.e., less than 1 minute. The response, however, is not necessarily transient. In order to study the effects of nuclear radiations on electronics systems and components, the transient radiation from a weapon is simulated in the laboratory by means of controlled sources of both steady-state and transient radiations.

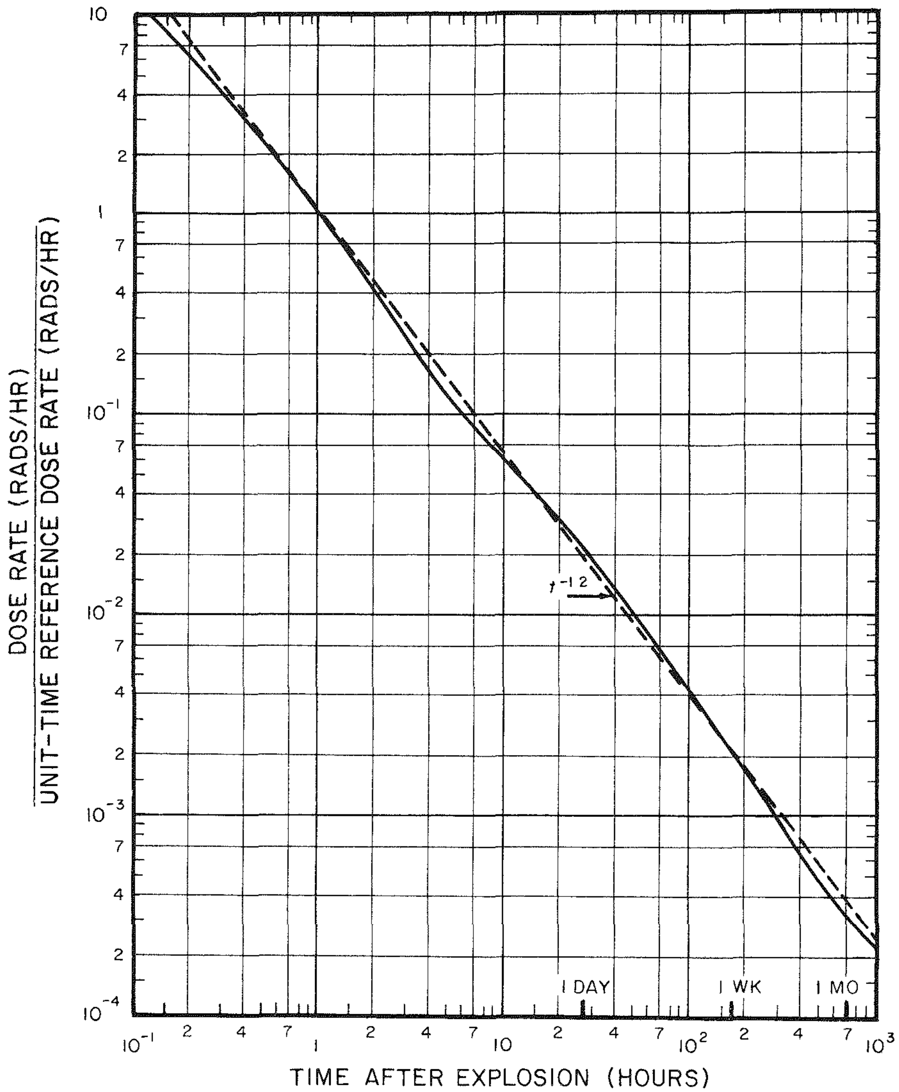

Figure 9.16a. Dependence of dose rate from early fallout upon time after explosion.

nated with fallout. Because the internal doses are highly dependent upon the circumstances, they are not predictable.

9.17 Suppose, for example, that at a given location, the fallout commences at 5 hours after the explosion, and that at 15 hours, when the fallout has ceased to descend, the observed (external) dose rate is 4.0 rads per hour (rads/hr). From the curve in Fig. 9.16a (or the data in Table 9.19), it is seen that at 15 hours after the explosion, the ratio of the actual dose rate to the reference value is 0.040; hence, the reference dose rate must be 4.0/0.040=100 rads/hr. By means of this reference value and the

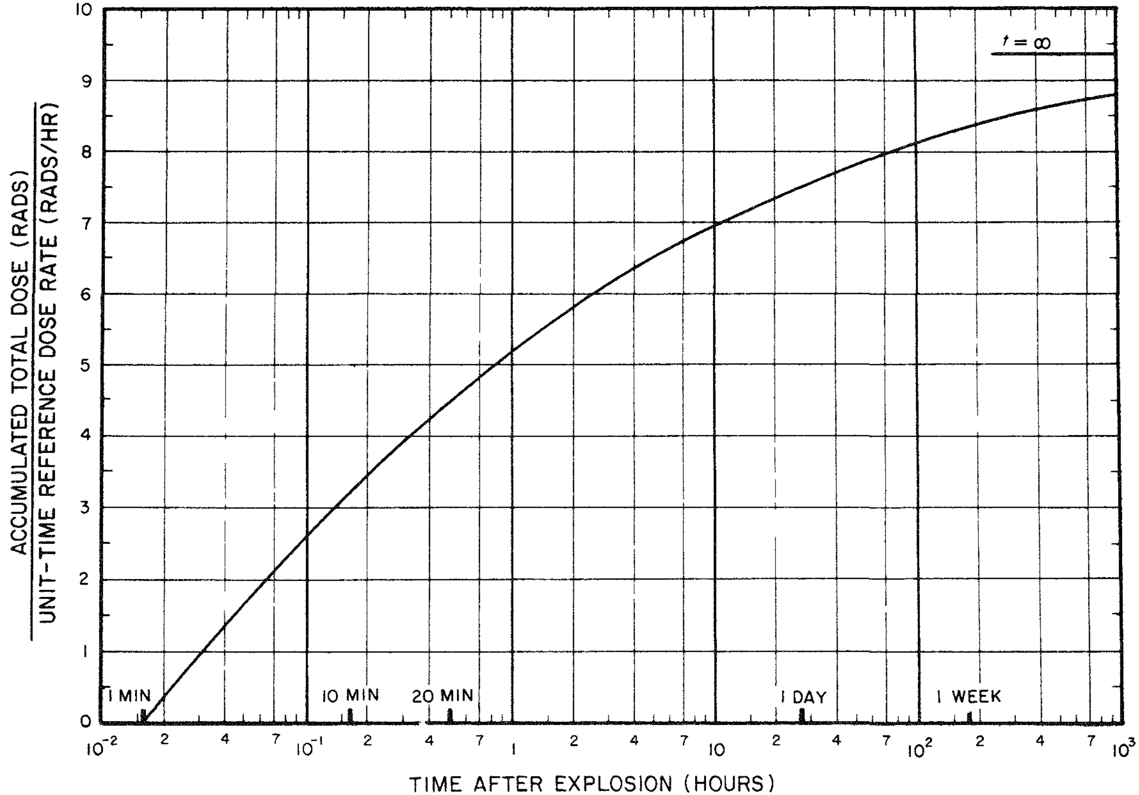

Figure 9.20. Curve for calculating accumulated total dose from early fallout at various times after explosion.

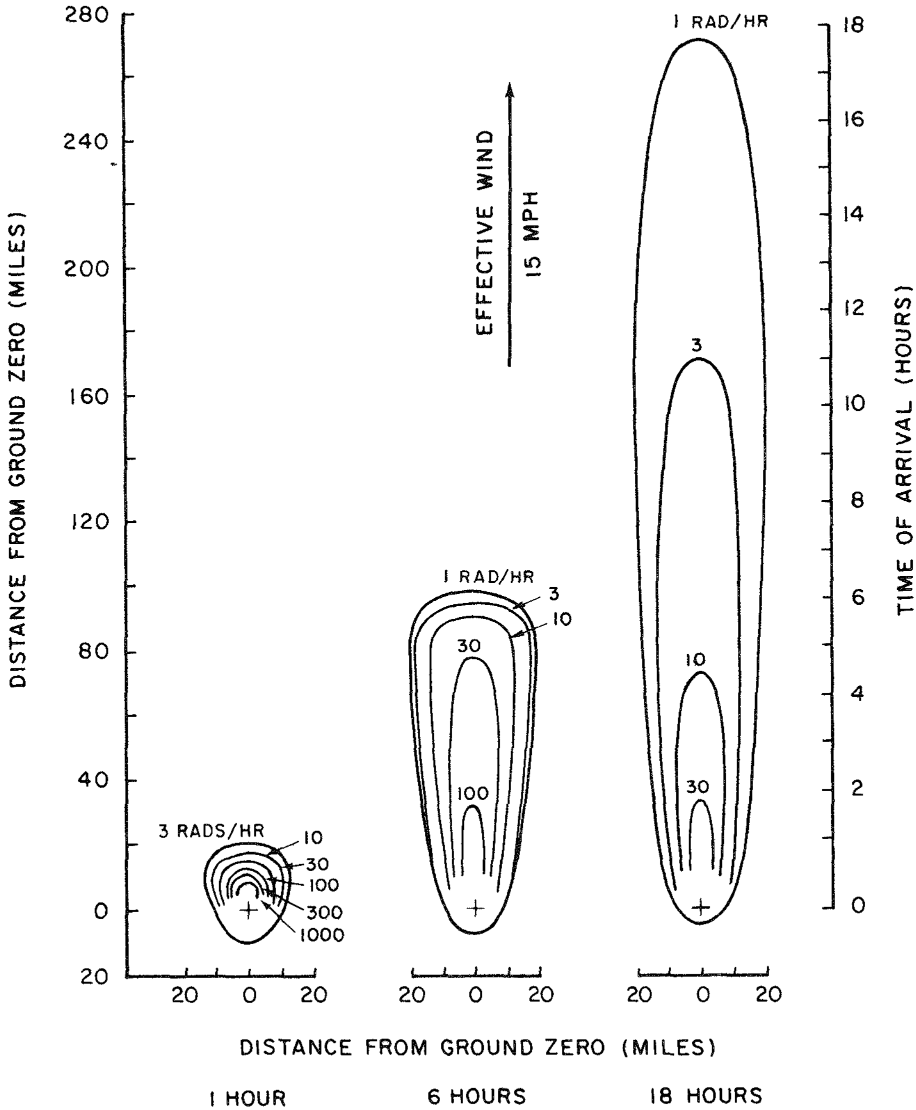

Figure 9 86a Dose-rate contours from early fallout at 1, 6, and 18 hours after a surface burst with a total yield of 2 megatons and 1 megaton fission yield (15 mph effective wind speed)

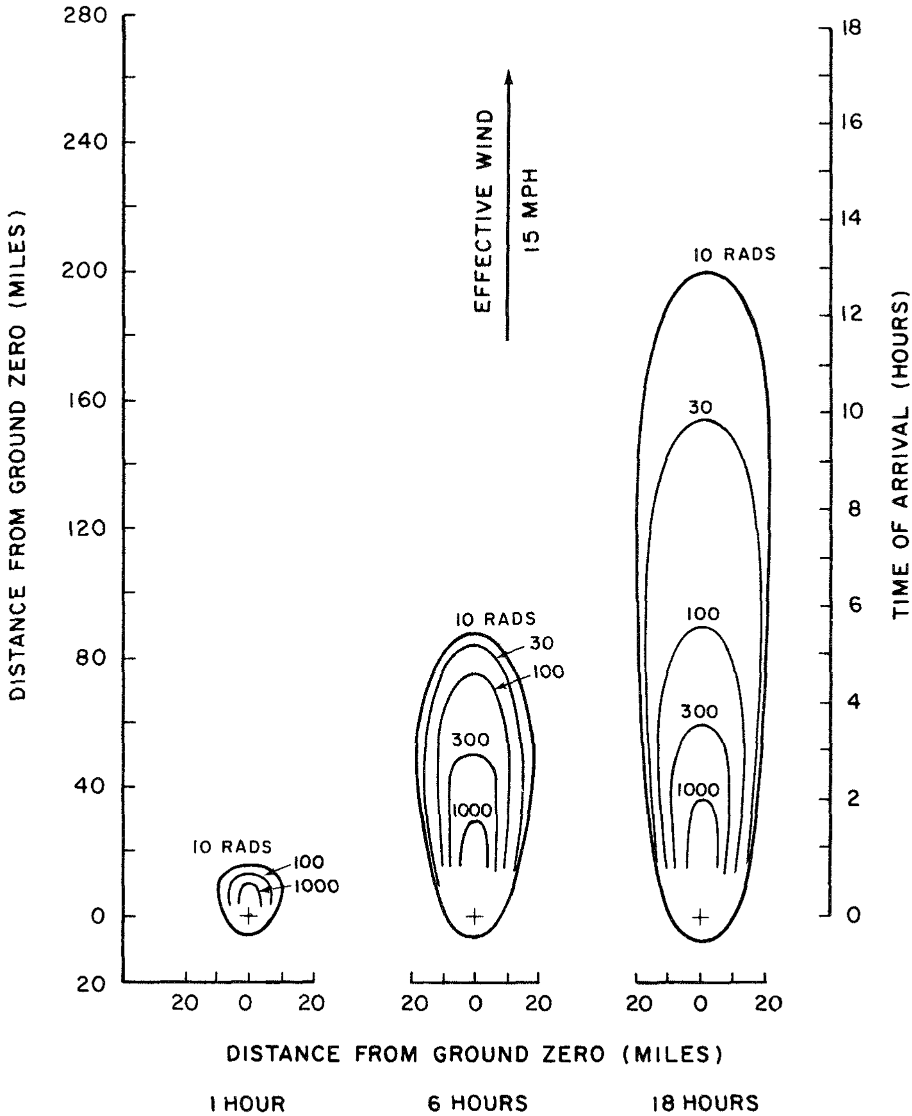

Figure 9.86b. Total-dose contours from early fallout at 1, 6, and 18 hours after a surface burst with a total yield of 2 megatons and 1-megaton fission yield (15 mph effective wind speed).

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Table 10.122

EFFECTS OF NUCLEAR DETONATIONS ON RADIO AND RADAR SYSTEMS

Frequency Band	Degradation Mechanism	Spatial Extent and Duration of Effects*	Comments
VLF	Phase changes, amplitude changes	Hundreds to thousands of miles, minutes to hours	Ground wave not affected, lowering of sky wave reflection height causes rapid phase change with slow recovery Significant amplitude degradation of sky wave modes possible
LF	Absorption of sky waves, defocusing	Hundreds to thousands of miles, minutes to hours	Ground wave not affected, effects sensitive to relative geometry of burst and propagation path
MF	Absorption of sky waves, defocusing	Hundreds to thousands of miles, minutes to hours	Ground wave not affected
HF	Absorption of sky waves, loss of support for F region reflection, multipath interference	Hundreds to thousands of miles, burst region and conjugate, minutes to hours	Daytime absorption larger than nighttime, F-region disturbances may result in new modes, multipath interference
VHF	Absorption, multipath interference, or false targets resulting from resolved multipath radar signals	Few miles to hundreds of miles, minutes to tens of minutes	Fireball and D-region absorption, FPIS circuits may experience attenuation or multipath interference
UHF	Absorption	Few miles to tens of miles, seconds to few minutes	Only important for line-of-sight propagation through highly ionized regions

*The magnitudes of spatial extent and duration are sensitive functions of detonation altitude and weapon yield for production rates less than about 10^6 electrons cm^{-3} sec^{-1} For production rates of about 10^7 (or more) electrons cm^{-3} sec^{-1}, the electron density at 40 miles is given approximately by

$$N_e(t) \text{ at 40 miles} \approx 3 \times 10^3 \sqrt{q(t)} \text{ cm}^{-3},$$

for both daytime and nighttime This result is consistent with Figs 10 159a and b, in which the curves for day and night coincide when the circumstances are such as to lead to high electron densities The conditions of applicability of these figures, as described in § 10.160 *et seq*, also apply to the expressions given above

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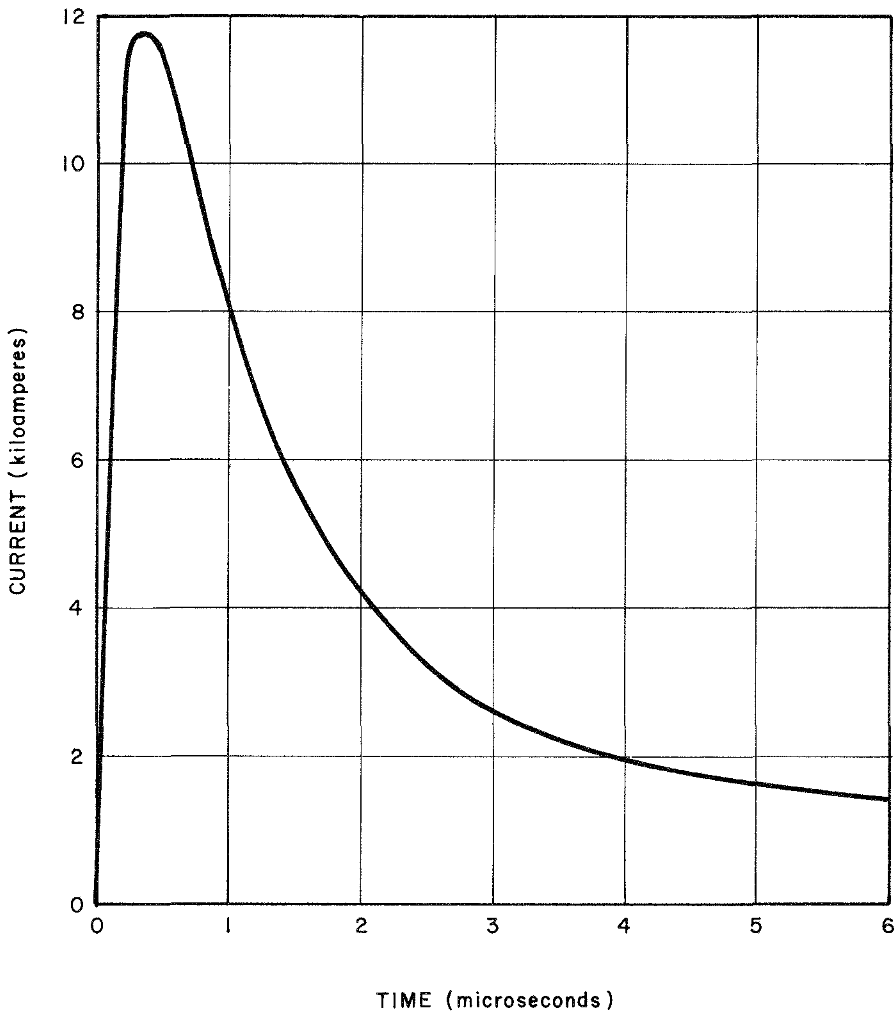

Figure 11.50. Typical form of the current pulse induced by the EMP from a high-altitude nuclear explosion in a long overhead power line. (The actual currents and times will depend to some extent on the conditions.)

high-altitude explosions than for lightning. Modern lightning arresters, however, can provide protection against EMP in many applications and hybrid arresters (§ 11.40) are expected to be even better.

11.51 In the absence of adequate protection, the surge voltages on overhead power lines produced by the EMP could cause insulator flashover, particularly on circuits of medium and low voltage. (The components of high-voltage transmission systems should be able to withstand the EMP surge voltages.) If ion region, for the lower-frequency EMP arising from differences in air density, the radiated electric field $E(t)$ at any specified time t as observed at a distance R from the burst point is given by

$$E(t) = \frac{R_0}{R} E_0(t) \sin \theta, \tag{11.67.1}$$

where R_0 is the radius of the deposition region, $E_0(t)$ is the radiated field strength at the distance R_0, i.e., at the beginning of the radiating region, at the time t, and θ is the angle between the vertical and a line joining the observation point to the burst point. It follows from equation (11.67.1) that, as stated in § 11.06, the EMP field strength is greatest in directions perpendicular to the (vertical) electron current. Values of E_0 (t) and R_0 are determined by computer calculations for specific situations; $E_0(t)$ is commonly from a few tens to a few hundred volts per meter and R_0 is from about 3 to 9 miles (§ 11.09). The interaction of the gamma rays with air falls off roughly exponentially with distance; hence, the deposition region does not have a precise boundary, but R_0 is taken as the distance that encloses a volume in which the conductivity is 10^{-7} mho per meter or greater.

SURFACE BURSTS

11.68 In a contact surface burst, the presence of the ground introduces a strong additional asymmetry. Compared with air, the ground is a very good absorber of neutrons and gamma rays and a good conductor of electricity. Therefore, the deposition region consists approximately of a hemisphere in the air and there is a net electron current with a strong component in the upward direction. Further, the conducting ground provides an effective return path for the electrons with the result that current loops are formed. That is, electrons travel outward from the burst in the air, then return toward the burst point through the higher conductivity ground. These current loops generate very large azimuthal magnetic fields that run clockwise around the burst point (looking down on the ground) in the deposition region, especially close to the ground (Fig. 11.10). At points very near the burst, the air is highly ionized and its conductivity exceeds the ground conductivity. The tendency for the conduction current to shift to the ground is therefore reduced, and the magnetic fields in the ground and in the air are decreased correspondingly.

11.69 Large electric and magnetic fields are developed in the ground which contribute to the EMP, in addition to the fields arising from the deposition region. As a result of the number of variables that can affect the magnitude and shape of the fields, it is not possible to describe them in a simple manner. The peak radiated fields at the boundary of the deposition region are ten to a hundred times stronger in a direction along the earth than for a similar air burst. The variation with distance of the *peak* radiated electric field along the earth's surface is given by

$$E = \frac{R_0}{R} E_0 , \tag{11.69.1}$$

where E_0 is the peak radiated field at the radius R_0 of the deposition region and E is the peak field at the surface distance R from the burst point. For observation

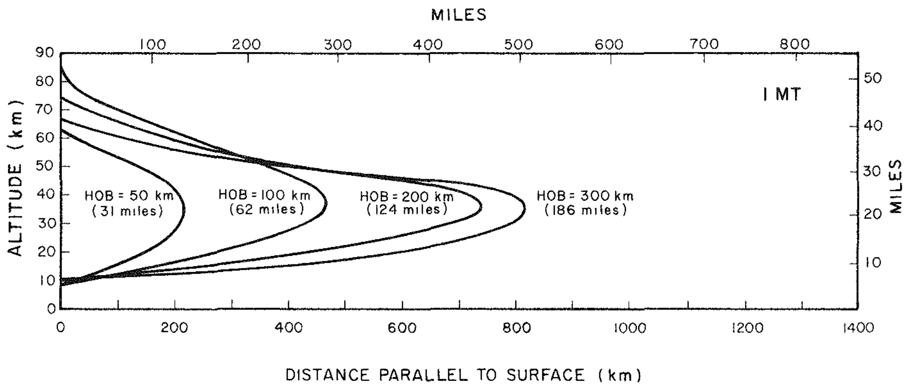

Figure 11.70a. Deposition regions for 1-MT explosions at altitudes of 31, 62, 124, and 186 miles.

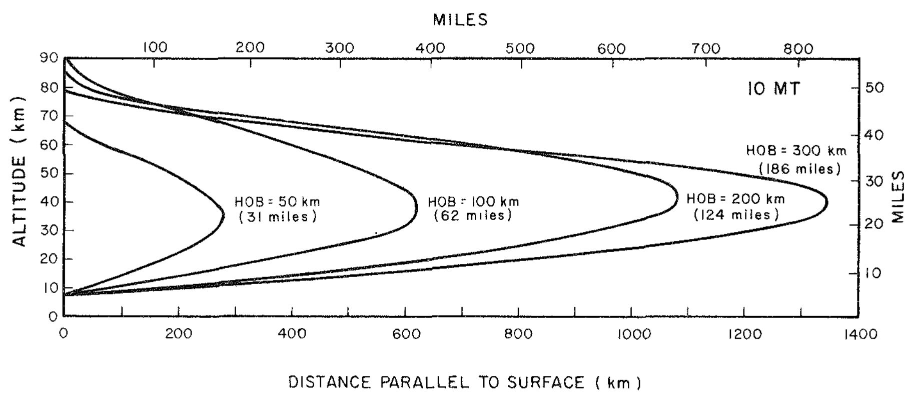

Figure 11.70b. Deposition regions for 10-MT explosions at altitudes of 31, 62, 124, 186 miles.

points above the surface the peak radiated field falls off rapidly with increasing distance. As stated in § 11.12, R_0 is roughly 2 to 5 miles, depending on the explosion yield; E_0 may be several kilovolts per meter.

HIGH-ALTITUDE BURSTS

11.70 The thickness and extent of half of the deposition region for bursts of 1 and 10 megatons yield, respectively, for various heights of burst (HOB) are shown in Figs. 11.70a and b. The abscissas are distances in the atmosphere measured parallel to the earth's surface from ground zero. The curves were computed from the estimated gamma-ray emissions from the explosions and the known absorption coefficients of the air at various densities (or altitudes). At small ground distances, i.e., immediately below the burst, the deposition region is thicker than at larger distances because the gamma-ray intensity decreases with distance from the burst point. Since the gamma rays pass through air of increasing density as they travel toward the ground, most are absorbed in a layer between altitudes of roughly 40 and 10 miles.

11.71 Unless they happen to be ejected along the lines of the geomagnetic field, the Compton electrons resulting from the interaction of the gamma-ray photons with the air molecules and atoms in the deposition region will be forced to follow curved paths along the field lines.[3] In doing so they are subjected to a radial acceleration and the ensemble of turning electrons, whose density varies with time, emits electromagnetic radiations which add coherently. The EMP produced in this manner from a high-altitude burst—and also to some extent from an air burst—is in a higher frequency range than the EMP arising from local asymmetries in moderate-altitude and surface bursts (§ 11.63).

11.72 The curves in Figs. 11.70a and b indicate the dimensions of the deposition (source) region, but they do not show the extent of coverage on (or near) the earth's surface. The EMP does not radiate solely in a direction down from the source region; it also radiates from the edges and at angles other than vertical beneath this region. Thus, the effect at the earth's surface of the higher-frequency EMP extends to the horizon (or tangent point on the surface as viewed from the burst). The lower frequencies, however, will extend even beyond the horizon because these electromagnetic waves can follow the earth's curvature (cf. § 10.92). Table 11.72 gives the distances along the surface from ground zero to the tangent point for several burst heights.

Table 11.72

GROUND DISTANCE TO TANGENT POINT FOR VARIOUS BURST ALTITUDES

Burst Altitude (miles	Tangent Distance (miles)
62	695
93	850
124	980
186	1,195
249	1,370
311	1,520

11.73 The peak electric field (and its amplitude) at the earth's surface from a high-altitude burst will depend upon the explosion yield, the height of burst, the location of the observer, and the orientation with respect to the geomagnetic field. As a general rule, however, the field strength may be expected to be tens of kilovolts per meter over most of the area receiving the EMP radiation. Figure 11.73 shows computed contours for E_{max}, the maximum peak electric field, and various fractions of E_{max} for burst altitudes between roughly 60 and 320 miles, assuming a yield of a few hundred kilotons or more. The distances, measured along the earth's surface, are shown in terms of the height of burst. The spatial distribution of the EMP electric field depends on the geomagnetic field and so varies with the latitude; the results in the figures apply generally for ground zero between about 30° and 60° north latitude. South of the geomagnetic equator the directions indicating magnetic north and east in the figure would become south and west, respectively. It is evident from Fig.

[3] At higher altitudes, when the atmospheric density is much less and collisions with air atoms and molecules are less frequent, continued turning of the electrons (beta particles) about the field lines leads to the helical motion referred to in §§ 2.143, 10.27.

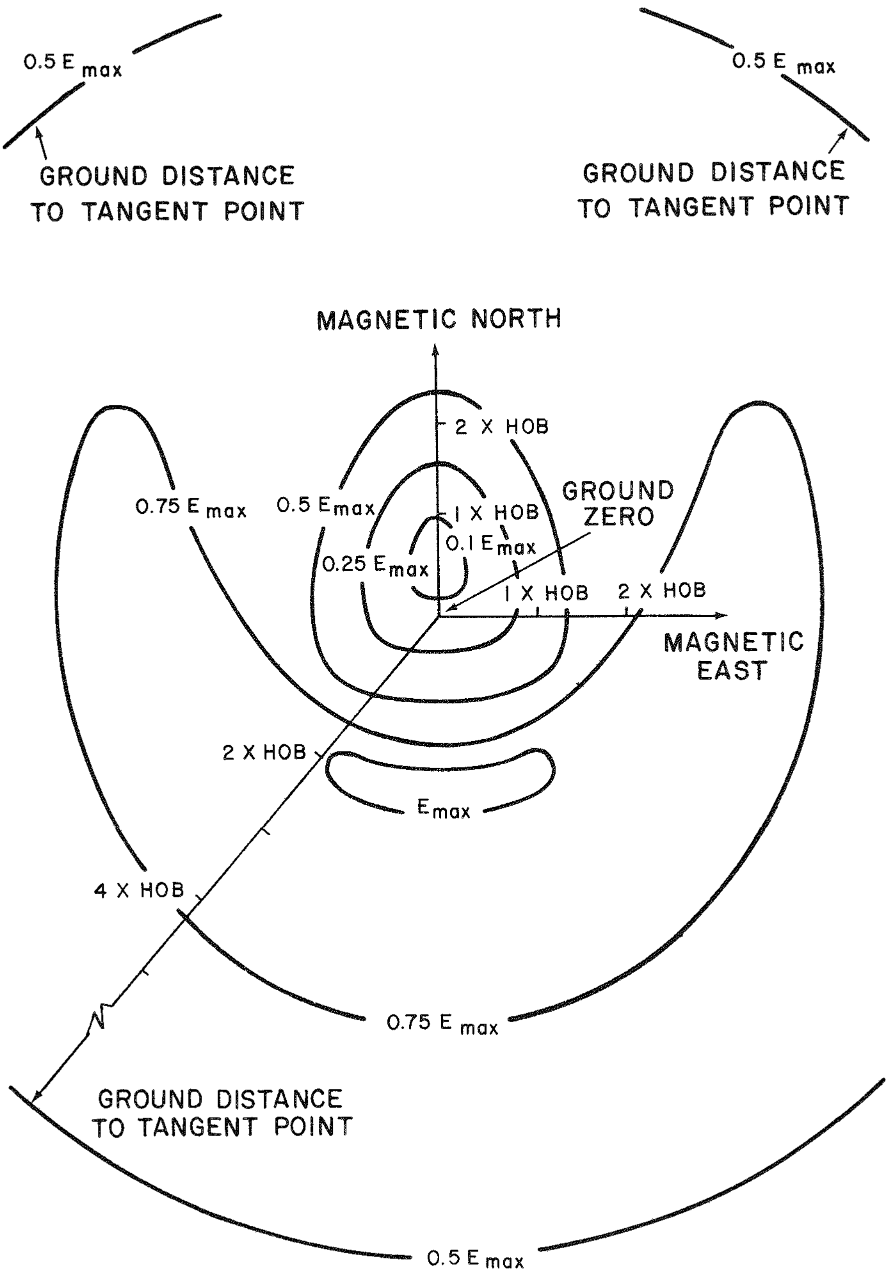

Figure 11.73. Variations in peak electric fields for locations on the earth's surface for burst altitudes between 60 and 320 miles and for ground zero between 30° and 60° north latitude. The data are applicable for yields of a few hundred kilotons or more.

11.73 that over most of the area affected by the EMP the electric field strength on the ground would exceed $0.5E_{max}$. For yields of less than a few hundred kilotons, this would not necessarily be true because the field strength at the earth's tangent could be substantially less than $0.5\ E_{max}$

11.74 The reason why Fig 11.73 does not apply at altitudes above about 320 miles is that at such altitudes the tangent range rapidly becomes less than four times the height of burst. The distance scale in the figure, in terms of the HOB, then ceases to have any meaning. For heights of burst above 320 miles, a set of contours similar to those in Fig. 11.73 can be plotted in terms of fractions of the tangent distance.

11.75 The spatial variations of EMP field strength arise primarily from the orientation and dip angle of the geomagnetic field, and geometric factors related to the distance from the explosion to the observation point. The area of low field strength slightly to the north of ground zero in Fig. 11.73 is caused by the dip in the geomagnetic field lines with reference to the horizontal direction. Theoretically, there should be a point of zero field strength in the center of this region where the Compton electrons would move directly along the field lines without turning about them, but other mechanisms, such as oscillations within the deposition region, will produce a weak EMP at the earth's surface. The other variations in the field strength at larger ground ranges are due to differences in the slant range from the explosion.

11.76 The contours in Fig. 11.73 apply to geomagnetic dip angles of roughly 50° to 70°. Although E_{max} would probably not vary greatly with the burst latitude, the spatial distribution of the peak field strength would change with the dip angle. At larger dip angles, i.e., at higher latitudes than about 60°, the contours for E_{max} and $0.75\ E_{max}$ would tend more and more to encircle ground zero. Over the magnetic pole (dip angle 90°), the contours would be expected theoretically to consist of a series of circles surrounding ground zero, with the field having a value of zero at ground zero. At lower dip angles, i.e., at latitudes less than about 30°, the tendency for the contours to become less circular and to spread out, as in Fig 11.73, would be expected to increase.

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*These documents may be purchased from the National Technical Information Service, Department of Commerce, Springfield, Virginia 22161 was less for persons in residential (wood-frame and plaster) structures and least of all for those in concrete buildings. These facts emphasize the influence of circumstances of exposure on the casualties produced by a nuclear weapon and indicate that shielding of some type can be an important factor in survival. For example, within a range of 0.6 mile from ground zero over 50 percent of individuals in Japanese-type homes probably died of nuclear radiation effects, but such deaths were rare among persons in concrete buildings within the same range. The effectiveness of concrete structures in providing protection from injuries of all kinds is apparent from the data in Table 12.17; this gives the respective average distances from ground zero at which there was 50-percent survival (for at least 20 days) among the occupants of a number of buildings in Hiroshima. School personnel who were indoors had a much higher survival probability than those who were outdoors at the times of the explosions.

Table 12.17

AVERAGE DISTANCES FOR 50-PERCENT SURVIVAL AFTER 20 DAYS IN HIROSHIMA

	Approximate Distance (miles)
Overall	0.8
Concrete buildings	0.12
School personnel:	
Indoors	0.45
Outdoors	1.3

CAUSES OF INJURIES AMONG SURVIVORS

12.18 From surveys made of a large number of Japanese, a fairly good idea has been obtained of the distribution of the three types of injuries among those who became casualties but survived the nuclear attacks. The results are quoted in Table 12.18; the totals add up to more than 100 percent, since many individuals suffered multiple injuries.

Table 12.18

DISTRIBUTION OF TYPES OF INJURY AMONG SURVIVORS

Injury	Percent of Survivors
Blast (mechanical)	70
Burns (flash and flame)	65
Nuclear radiation (initial)	30

12.19 Among survivors the proportion of indirect blast (mechanical) injuries due to flying missiles and motion of other debris was smallest outdoors and largest in certain types of industrial buildings. Patients were treated for lacerations received out to 10,500 feet (2 miles) from ground zero in Hiroshima and out to 12,500 feet (2.2 miles) in Nagasaki. These distances correspond roughly to those at which moderate damage occurred to wood-frame houses, including the shattering of window glass.

12.20 An interesting observation made among the Japanese survivors was the relatively low incidence of serious mechanical injuries. For example, fractures were found in only about 4 percent of survivors. In one hospital there were no cases of fracture of the skull or back and only one fractured femur among 675 patients, although many such injuries must have undoubtedly occurred. This was attributed to the fact that persons who suffered severe concussion or fractures were rendered helpless, particularly if leg injuries occurred, and, along with those who were pinned beneath the wreckage, were trapped and unable to seek help or escape in case fire ensued. Such individuals, of course, did not survive.

CASUALTIES AND STRUCTURAL DAMAGE

12.21 For people who were in buildings in Japan, the overall casualties were related to the extent of structural damage, as well as to the type of structure (§ 12.17). The data in Table 12.21 were obtained from a study of 1,600 Japanese who were in reinforced-concrete buildings, between 0.3 and 0.75 mile from ground zero, when the nuclear explosions occurred. At these distances fatalities in the open ranged from about 90 to 100 percent, indicating, once more, that people were safer inside buildings, even when no special protective action was taken because of the lack of warning. There may have been an increase of casualties in buildings from debris etc., but this was more than compensated by the reduction due to shielding against the initial nuclear radiation and particularly from the thermal pulse.

12.22 In two concrete buildings closest to ground zero, where the mortality rate was 88 percent, about half the casualties were reported as being early and the other half as delayed. The former were attributed to a variety of direct and indirect blast injuries, caused by overpressure, structural collapse, debris, and whole-body translation, whereas the latter were ascribed mainly to burns and initial nuclear radiation. Minor to severe but nonfatal blast injuries no doubt coexisted and may have contributed to the delayed lethality in many cases. At greater distances, as the threat from nuclear radiation decreased more rapidly than did that from air blast and thermal radiation, the proportion of individuals with minor injuries or who were uninjured increased markedly. The distribution of casualties of different types in Japanese buildings was greatly influenced by where the people happened to be at the time of the explosion. Had they been forewarned and knowledgeable about areas of relative hazard and safety, there would probably have

Table 12.21

CASUALTIES IN REINFORCED-CONCRETE BUILDINGS IN JAPAN RELATED TO STRUCTURAL DAMAGE

	Percent of Individuals			
Structural Damage	Killed Outright	Serious Injury (hospitalization)	Light Injury (no hospitalization)	No Injury Reported
Severe damage	88	11	—	1
Moderate damage	14	18	21	47
Light damage	8	14	27	51

been fewer casualties even in structures that were badly damaged.

12.23 The shielding effect of a particular building is not only different for blast, the thermal pulse, and nuclear radiation, but it may also depend on the distance from the explosion and the height of burst. Furthermore, the locations and orientations of individuals in the building are important in determining the extent of the shielding. Hence, the protection offered by structures is quite variable. This fact must be kept in mind in considering the data in Table 12.21. Although the table indicates a general correlation between structural damage and the frequency of casualties, the numbers cannot be used to estimate casualties from the degree of structural damage. In an actual situation, the effects would depend on many factors, including the type of structure, the yield of the nuclear explosion, the height of burst, the distance from the explosion point, the locations and orientations of people in the building, and the nature of prior protective action.

BLAST INJURIES

DIRECT BLAST INJURIES: BIOLOGICAL FACTORS

12.24 Blast injuries are of two main types, namely, direct (or primary) injuries associated with exposure of the body to the environmental pressure variations accompanying a blast wave, and indirect injuries resulting from impact of penetrating and nonpenetrating missiles on the body or as the consequences of displacement of the body as a whole. There are also miscellaneous blast injuries, such as burns from the gases and debris, and irritation and possibly suffocation caused by airborne dust. The present section will treat direct injuries, and indirect blast effects will be discussed later.

12.25 The general interactions of a human body with a blast wave are somewhat similar to that of a structure as described in Chapter IV. Because of the relatively small size of the body, the diffraction process is quickly over, the body being rapidly engulfed and subjected to severe compression. This continues with decreasing intensity for the duration of the positive phase of the blast wave. At the same time the blast wind exerts a drag force of considerable magnitude which contributes to the displacement hazard.

12.26 The sudden compression of the body and the inward motion of the thoracic and abdominal walls cause rapid pressure oscillations to occur in the air-containing organs. These effects, together with the transmission of the shock wave through the body, produce damage mainly at the junctions of tissues with air-containing organs and at areas between tissues of different density, such as where cartilage and bone join soft tissue. The chief consequences are hemorrhage and occasional rupture of abdominal and thoracic walls.

12.27 The lungs are particularly prone to hemorrhage and edema (accumulation of fluid causing swelling), and if the injury is severe, air reaches the veins of the lungs and hence the heart and arterial circulation. Death can occur in a few minutes from air embolic obstruction of the vessels of the heart or the brain or from suffocation caused by lung hemorrhage or edema. Fibrin emboli in the blood may also affect the brain and other critical organs. The emboli, apparently associated with severe hemorrhagic damage to the lungs, are a consequence of the disturbance of the blood-clotting mechanism. Damage to the brain due to air blast overpressure alone is improbable, but indirect damage may arise from injury to the head caused by missiles, debris, or displacement of the body. Bodily activity after blast damage to the heart and lungs is extremely hazardous and lethality can result quickly where recovery might otherwise have been expected. The direct blast effect was not specifically recognized as a cause of fatality in Japan, but it no doubt contributed significantly to early mortality even though most of the affected individuals may also have received mortal injury from debris, displacement, fire, or thermal and nuclear radiations.

12.28 Primary blast casualties have been reported after large-scale air attacks with conventional high-explosive bombs, mainly because of the provision of medical care for those who otherwise would have suffered the early death that is characteristic of serious blast injury to the lungs. However, persons who spontaneously survive for 24 to 48 hours in the absence of treatment, complications, and other injury usually recover and show little remaining lung hemorrhage after 7 to 10 days. In very severe injuries under treatment, recurring lung hemorrhage has been reported as long as 5 to 10 days after injury. In view of such facts and overwhelming disruptive effects of the Japanese bombings on medical and rescue services, it can be concluded that individuals with significant direct blast injuries did not survive. Those with relatively minor blast injuries who did survive, did so without getting into medical channels, or if they did require medical care it was for post-blast complications, e.g., pneumonitis, or for causes other than blast injury to the lungs. For these reasons primary blast effects, except for eardrum rupture, were not commonly seen among Japanese survivors.

12.29 Many persons who apparently suffered no serious injury reported temporary loss of consciousness. This symptom can be due to the direct action of the blast wave, resulting from transient disturbance of the blood circulation in the brain by air emboli. However, it can also be an indirect effect arising from impact injury to the head caused by missiles or by violent displacement of the body by the air pressure wave.

12.30 A number of cases of ruptured eardrums were reported among the survivors in Hiroshima and Nagasaki, but the incidence was not high even for those who were fairly close to ground zero. Within a circle of 0.31 mile (1,640 feet) radius about 9 percent of a group of 44 survivors in Nagasaki had ruptured eardrums, as also did some 8 percent of 125 survivors in the ring from 0.31 to 0.62 mile from ground zero. In Hiroshima the incidence of ruptured eardrums was somewhat less. In both cities very few cases were observed beyond 0.62 mile.

DIRECT BLAST INJURIES: PHYSICAL FACTORS

12.31 Tests with animals have demonstrated that five parameters of the blast wave can affect the extent of the direct injuries to the body; they are (1) the ambient pressure, (2) the "effective" peak overpressure, (3) the rate of pressure rise (or "rise time") at the blast wave front, (4) the character and "shape" of the pressure pulse, and (5) the duration of the positive phase of the blast wave and the associated wind (see Chapter III). These parameters will be considered below as they arise.

12.32 The biologically effective peak overpressure depends on the orientation of the individual to the blast wave. If the subject is against a reflecting surface, e.g., a wall, the effective overpressure for direct blast injury is equal to the maximum reflected overpressure, which may be a few times the incident peak overpressure. On the other hand, in the open at a substantial distance from a reflecting surface, the effective overpressure is the sum of the peak incident overpressure and the associated peak dynamic pressure if the subject is perpendicular to the direction of travel of the blast wave and to the peak overpressure alone if the subject is parallel to this direction. Consequently, for a given incident overpressure, the blast injury is expected to be greatest if the individual is close to a wall and least if he is at a distance from a reflecting surface and is oriented with his body parallel to the direction in which the blast wave is moving.

12.33 The body, like many other structures, responds to the difference between the external and internal pressures. As a consequence, the injury caused by a certain peak overpressure depends on the rate of increase of the pressure at the blast wave front. For wave fronts with sufficiently slow pressure rise, the increase in internal pressure due to inward movement of the body wall and air flow in the lungs keeps pace (to some extent) with the external pressure. Consequently, quite high incident overpressures are tolerable. In contrast, if the rise time is short, as it is in nuclear explosions under appropriate terrain and burst conditions, the damaging effect of a given overpressure is greater. The increase in internal pressure of the body takes a finite time and the response is then to the maximum possible pressure differential. Thus, a sharply rising pressure pulse will be more damaging than if the same peak overpressure is attained more slowly. In precursor formation (§ 3.79 *et seq.*), for example, the blast pressure increases at first slowly and then quite rapidly; the injury potential of a given peak overpressure is thus decreased.

12.34 An individual inside a building but not too close to a wall would be subject to multiple reflections of the blast wave from the ceiling, floor, and walls as well as to the incident wave entering the structure. Since the reflected waves would reach him at different times, the result would be a step loading, although the rise time for each step might be quite short. In such cases, where the initial blast pressure is tolerable and the subsequent pressure increase is not too great or occurs in stages (or slowly), a certain peak overpressure is much less hazardous than if it were applied in a single sharp pulse. Apparently the reason for the decreased blast injury potential in these situations is that the early stage of the pressure pulse produces an increase in the internal body pressure, thereby reducing the pressure differential associated with the later portion of the pulse. In a manner of speaking, a new and higher "ambient" pressure is imposed on the body by the early part of the pressure pulse and tolerance to the later rise in overpressure is enhanced. A higher peak overpressure is then required to cause a certain degree of blast injury.

12.35 Clearly, for a given peak incident overpressure, the geometry[2] in which an individual is exposed inside a structure may have a significant effect on his response to air blast. A location against a wall is the most hazardous position because the effective peak overpressure, which is the maximum reflected overpressure, is high and is applied rapidly in a single step. A location a few feet from a wall is expected to decrease the direct blast injury, although the hazard arising from displacement of the body may be increased. Apart from the effects just described, oscillating pressures, for which no adequate biomedical criteria are available, often exist inside structures due to reverberating reflections from the inside walls.

12.36 The duration of the positive phase of the blast wave is a significant factor for direct blast injuries. Up to a point, the increase in the duration increases the probability of injury for a given effective peak overpressure. Beyond this point, which may be of the order of several tens to a few hundred milliseconds, depending on the body size, it is only the magnitude of the overpressure that is important. The duration of the positive phase, for a given peak overpressure, varies with the energy yield and the height of burst (§ 3.75 *et seq.*). But for most conditions, especially for energy yields in excess of about 10 kilotons, the duration of the positive phase of the blast wave is so long—approaching a second or more—that the effective peak overpressure is the main factor for determining the potential for direct injury from a fast-rising pressure pulse.

12.37 A given peak pressure in the blast wave from conventional high explosives is less effective than from a nuclear explosion—except perhaps at unusually low yields—mainly because of the short duration of the positive phase in the former case. From observations made with small charges of chemical explosives, it has been estimated that deaths in humans would require sharp-rising effective overpressures as high as 200 to 400 (or more) pounds per square inch when the positive phase durations are less than a millisecond or so. These pressures may be compared with values of roughly 50 (or less) to about 100 pounds per square inch, with positive phase durations of the order of a second, for nuclear explosions.

12.38 Tentative criteria, in terms of effective peak overpressure as defined in § 12.32, for lung damage, lethality, and eardrum rupture caused by a fast-rising pressure pulse of long duration (0.1 second or more) are given in Table 12.38. The values for lung damage and

[2] The word "geometry" is used here as a general term to describe the location of an individual in relation to the details of the environment that may affect the blast wave characteristics.

lethality are average pressures obtained by extrapolation from animal data to man; the variability of the results is indicated by the numbers in parentheses. Rupture of the normal eardrum is apparently a function of the age of the individual as well as of the effective blast pressure. Failures have been recorded at overpressures as low at 5 pounds per square inch ranging up to 40 or 50 pounds per square inch. The values in Table 12.38 of the effective peak overpressures for eardrum rupture are based on relatively limited data from man and animals.

INDIRECT BLAST INJURIES

12.39 Indirect blast injuries are associated with (1) the impact of missiles, either penetrating or nonpenetrating (secondary effects), and (2) the physical displacement of the body as a whole (tertiary effects). The wounding potential of blast debris depends upon a number of factors; these include the impact (or striking) velocity, the angle at which impact occurs, and the size, shape, density, mass, and nature of the moving objects. Furthermore, consideration must be given to the portion of the body involved in the missile impact, and the events which may occur at and after the time of impact, namely, simple contusions and lacerations, at one extreme, or more serious penetrations, fractures, and critical damage to vital organs, at the other extreme.

12.40 The hazard from displacement depends mainly upon the time and distance over which acceleration and deceleration of the body occur. Injury is more likely to result during the latter phase when the body strikes a solid object, e.g., a wall or the ground. The velocity which has been attained before impact is then significant. This is determined by certain physical parameters of the blast wave, as mentioned below, as well as by the orientation of the body with respect to the direction of motion of the wave. The severity of the damage depends on the magnitude of the impact velocity, the properties of the impact

Table 12.38

TENTATIVE CRITERIA FOR DIRECT (PRIMARY) BLAST EFFECTS IN MAN FROM FAST-RISING, LONG-DURATION PRESSURE PULSES

Effect	Effective Peak Pressure (psi)
Lung Damage	
Threshold	12 (8–15)
Severe	25 (20–30)
Lethality	
Threshold	40 (30–50)
50 percent	62 (50–75)
100 percent	92 (75–115)
Eardrum Rupture	
Threshold	5
50 percent	15–20 (more than 20 years old)
	30–35 (less than 20 years old)

surface, and the particular portion of the body that has received the decelerative impact, e.g., head, back, extremities, thoracic and abdominal organs, body wall, etc.

DISPLACEMENT VELOCITIES

12.41 Because the effects of both missiles and body displacement depend on the velocity attained before impact, it is convenient to consider the relationships between displacement velocity and the blast parameters for objects as small as tiny pieces of glass and as large as man. The significant physical factors in all cases are the magnitude and duration of the blast overpressure and the accompanying winds, the acceleration coefficient of the displaced object,[3] ground shock, gravity, and the distance traveled by the object. The latter is important because, as a result of the action of the blast wave, the velocity of the object increases with the time and distance of travel until it attains that of the blast wind. Subsequently, the velocity falls because of negative winds or impact with the ground or other material.

12.42 As a result of the interaction of the various factors, large and heavy objects gain velocity rather slowly and attain a maximum velocity only after most of the blast wave has passed. The velocity is consequently determined by the duration of the overpressure and winds. In contrast, small and light objects reach their maximum velocity fairly quickly, often after a small proportion of the blast wave has passed over them. The maximum velocity is thus not too sensitive to the duration of the overpressure and winds, but depends largely on the effective peak overpressure (cf. § 12.32). As a consequence of this fact, it has been found possible to relate the velocities attained by the fragments produced by the breakage of glass window panes to the effective overpressure. The results for glass panes of different thicknesses can be expressed in a fairly simple graphical manner as will be shown in § 12.238.

12.43 The variations of the overpressure and dynamic pressure with time (§ 3.57 *et seq.*) at the location of interest also have a bearing on the behavior of a displaced object. Data were obtained at nuclear weapons tests under such conditions that the blast wave was approximately ideal in behavior. Some of the median velocities, masses, and spatial densities (number of fragments per square foot) of window glass, from houses exposed to the blast, and of natural stones are summarized in Table 12.43. For glass, the velocities refer to those attained after 7 to 13 feet of travel; for the stones the distances are not known, but the velocities given in the table may be regarded as applicable to optimum distances of missile travel.

12.44 Studies have also been made of the displacement of anthropomorphic dummies weighing 165 pounds by the blast from a nuclear explosion. A dummy standing with its back to the blast attained its maximum velocity, about 21 feet per second, after a displacement of 9 feet within 0.5 second after the arrival of the blast wave. The free-field overpressure at the test loca-

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[3]The acceleration coefficient is the product of the projected area presented to the blast wave and the drag coefficient (§ 4.19) divided by the mass of the object.

Table 12.43

VELOCITIES, MASSES, AND DENSITIES OF MISSILES

Missile	Peak Overpressure (psi)	Median Velocity (ft/sec)	Median Mass (grams)	Maximum Number per Sq Ft
Glass	1 9	108	1 45	4 3
Glass	3 8	168	0 58	159
Glass	3 9	140	0 32	108
Glass	5 0	170	0 13	388
Stones	8 5	286	0 22	40

tion was 5.3 pounds per square inch. The dummy traveled 13 feet before striking the ground and then slid or rolled another 9 feet. A prone dummy, however, did not move under the same conditions. The foregoing results were obtained in a situation where the blast wave was nearly ideal, but in another test, at a peak overpressure of 6.6 pounds per square inch, where the blast wave was nonideal (§ 3.79), both standing and prone dummies suffered considerably greater displacements. Even in such circumstances, however, the displacement of over 125 feet for the prone dummy was much less than that of about 250 feet for the standing one. The reason for the greater displacement of the standing dummy is that it acquired a higher velocity.

12.45 In order to study the displacements of moving objects, field tests have been made by dropping animal cadavers, including guinea pigs, rabbits, goats, and dogs, and stones and concrete blocks onto a flat, hard surface from a vehicle traveling between 10 and 60 miles per hour (14.7 to 88 feet per second). For a given initial velocity, the stopping distance for the animals increased somewhat with the mass, and a relationship was found to represent the stopping distance as a function of velocity applicable to the animals over a wide range of mass (§ 12.239). One reason for the consistency of the data is probably that all the animals assumed a rolling position about their long axis regardless of the initial orientation. The animals remained relatively low to the ground and bounced very little. By contrast, stones and concrete blocks bounced many times before stopping; the data were not sensitive to mass, depended more on orientation, and were more variable than the results obtained with animals. On the whole, the stopping distances of the blocks and stones were greater for a given initial velocity. One of the conclusions drawn from the foregoing tests was that a person tumbling over a smooth surface, free from rocks and other hard irregularities, might survive, even if the initial velocity is quite high, if he could avoid head injury and did not flail his limbs.

MISSILE AND DISPLACEMENT INJURY CRITERIA

12.46 Velocity criteria for the production of skin lacerations by penetrating missiles, e.g , glass fragments, are not known with certainty. Some reliable information is available, however, concerning the probability of penetration of the abdominal wall by glass. The impact velocities, for glass fragments of different masses, corresponding to 1, 50, and 99 percent penetration probability are recorded in Table 12.46.

12.47 The estimated impact velocities of a 10-gram (0.35-ounce) glass missile required to produce skin lacerations and serious wounds are summarized in Table 12.47 The threshold value for skin lacerations is recorded as 50 feet per second and for serious wounds it is 100 feet per second

12.48 Little is known concerning the relationship between mass and velocity of nonpenetrating missiles that will cause injury after impact with the body. Studies with animals showed that fairly high missile velocities are required to produce lung hemorrhage, rib fractures, and early mortality, but quantitative data for man are lacking. No relationship has yet been developed between mass and velocity of nonpene-

Table 12.46

PROBABILITIES OF GLASS FRAGMENTS PENETRATING ABDOMINAL WALL

Mass of Glass Fragments (grams)	Probability of Penetration (percent)		
	1	50	99
	Impact Velocity (ft/sec)		
0 1	235	410	730
0 5	160	275	485
1 0	140	245	430
10 0	115	180	355

Table 12.47

TENTATIVE CRITERIA FOR INDIRECT (SECONDARY) BLAST EFFECTS FROM PENETRATING 10-GRAM GLASS FRAGMENTS[4]

Effect	Impact Velocity (ft/sec)
Skin laceration	
Threshold	50
Serious wounds	
Threshold	100
50 percent	180
Near 100 percent	300

[4] Figures represent impact velocities with unclothed skin A serious wound is arbitrarily defined as a laceration of the skin with missile penetration into the tissues to a depth of 1 cm (about 0 4 inch) or more

trating missiles that will cause injury as a result of impacts with other parts of the body wall, particularly near the spine, kidney, liver, spleen and pelvis. It appears, however, that a missile with a mass of 10 pounds striking the head at a velocity of about 15 feet per second or more can cause skull fracture. For such missiles it is unlikely that a significant number of dangerous injuries will occur at impact velocities of less than 10 feet per second. The impact velocities of a 10-pound missile for various effects on the head are given in Table 12.48.

12.49 Although there may be some hazard associated with the accelerative phase of body displacement (translation) by a blast wave, the deceleration, particularly if impact with a solid object is involved, is by far the more significant. Since a hard surface will cause a more serious injury than a softer one, the damage criteria given below refer to perpendicular impact of the displaced body with a hard, flat object. From various data it is concluded that an impact velocity of 10 feet per second is unlikely to be associated with a significant number of serious injuries; between 10 and 20 feet per second some fatalities may occur if the head is involved; and above 20 feet per second, depending on trauma to critical organs, the probabilities of serious and fatal injuries increase rapidly with increasing displacement velocity. Impact velocities required to produce various indirect (tertiary) blast effects are shown in Table 12.49. The curves marked "translation near structures" in Fig. 12.49 may be used to estimate ground distances at which 1 percent and 50 percent casualties would be expected, as functions of height of burst, for a 1-kiloton explosion.[5] Based on tests with animals, the criteria for 1 and 50 percent casualties were somewhat arbitrarily set at impact velocities of 8 and 22 feet per second, respectively. The results in Fig. 12.49 may be extended to other burst heights and yields by using the scaling law given in the example facing the figure.

Table 12.48

TENTATIVE CRITERIA FOR INDIRECT BLAST EFFECTS INVOLVING NONPENETRATING 10-POUND MISSILES

Effect	Impact Velocity (ft/sec)
Cerebral Concussion:	
Mostly "safe"	10
Threshold	15
Skull Fracture:	
Mostly "safe"	10
Threshold	13
Near 100 percent	23

[5] In this connection, a casualty is defined as an individual so injured that he would probably be a burden on others. Some of the casualties would prove fatal, especially in the absence of medical care.

Table 12.49

TENTATIVE CRITERIA FOR INDIRECT (TERTIARY) BLAST EFFECTS INVOLVING IMPACT

Effect	Impact Velocity (ft/sec)
Standing Stiff-Legged Impact:	
Mostly "safe"	
No significant effect	< 8
Severe discomfort	8–10
Injury	
Threshold	10–12
Fracture threshold (heels, feet, and legs)	13–16
Seated Impact:	
Mostly "safe"	
No effect	< 8
Severe discomfort	8–14
Injury	
Threshold	15–26
Skull Fracture:	
Mostly "safe"	10
Threshold	13
50 percent	18
Near 100 percent	23
Total Body Impact:	
Mostly "safe"	10
Lethality threshold	21
Lethality 50 percent	54
Lethality near 100 percent	138

12.50 Evaluation of human tolerance to decelerative tumbling during translation in open terrain is more difficult than for impact against a rigid surface described above. Considerably fewer data are available for decelerative tumbling than for body impact, and there is virtually no human experience for checking the validity of extrapolations from observations on animal cadavers. Tests have been made with goats, sheep, and dogs, but for humans the information required to derive reliable hazards criteria for decelerative tumbling are still not adequate. The initial velocities at which 1 and 50 percent of humans are expected to become casualties as a result of decelerative tumbling have been tentatively estimated to be 30 and 75 feet per second, respectively. The curves in Fig. 12.49 marked "translation over open terrain" are approximate, but they may be used to provide a general indication of the range within which casualties might occur from decelerative tumbling due to air blast from surface and air bursts.

(Text continued on page 560.)

The curves in Fig. 12.49 show 50 percent and 1 percent casualties resulting from translation near structures and over open terrain as a function of ground distance and height of burst for a 1 KT explosion in a standard sea-level atmosphere. The results apply to randomly oriented, prone personnel exposed to the blast wave in the open. The curves for translation over open terrain (decelerative tumbling) are approximate (§ 12.50).

Scaling. The required relationships are

$$\frac{d}{d_1} = \frac{h}{h_1} = W^{0.4}$$

where d_1 and h_1 are the distance from ground zero and height of burst, respectively, for 1 KT; and d and h are the corresponding distance and height of burst for W KT.

Example

Given: A 50 KT explosion at a height of 860 feet over open terrain.

Find: The ground distance at which translational effects would produce 50 percent casualties among prone personnel.

Solution: The corresponding burst height for 1 KT is

$$h_1 = \frac{h}{W^{0.4}} = \frac{860}{(50)^{0.4}} = 180 \text{ feet.}$$

From Fig. 12.49, at a height of burst of 180 feet, the ground distance at which 50 percent casualties among personnel in the open will occur is roughly 660 feet. The corresponding ground distance for 50 KT is then given approximately as

$$d = d_1 W^{0.4} = 660 \times (50)^{0.4}$$
$$= 3{,}150 \text{ feet.} \quad \textit{Answer}$$

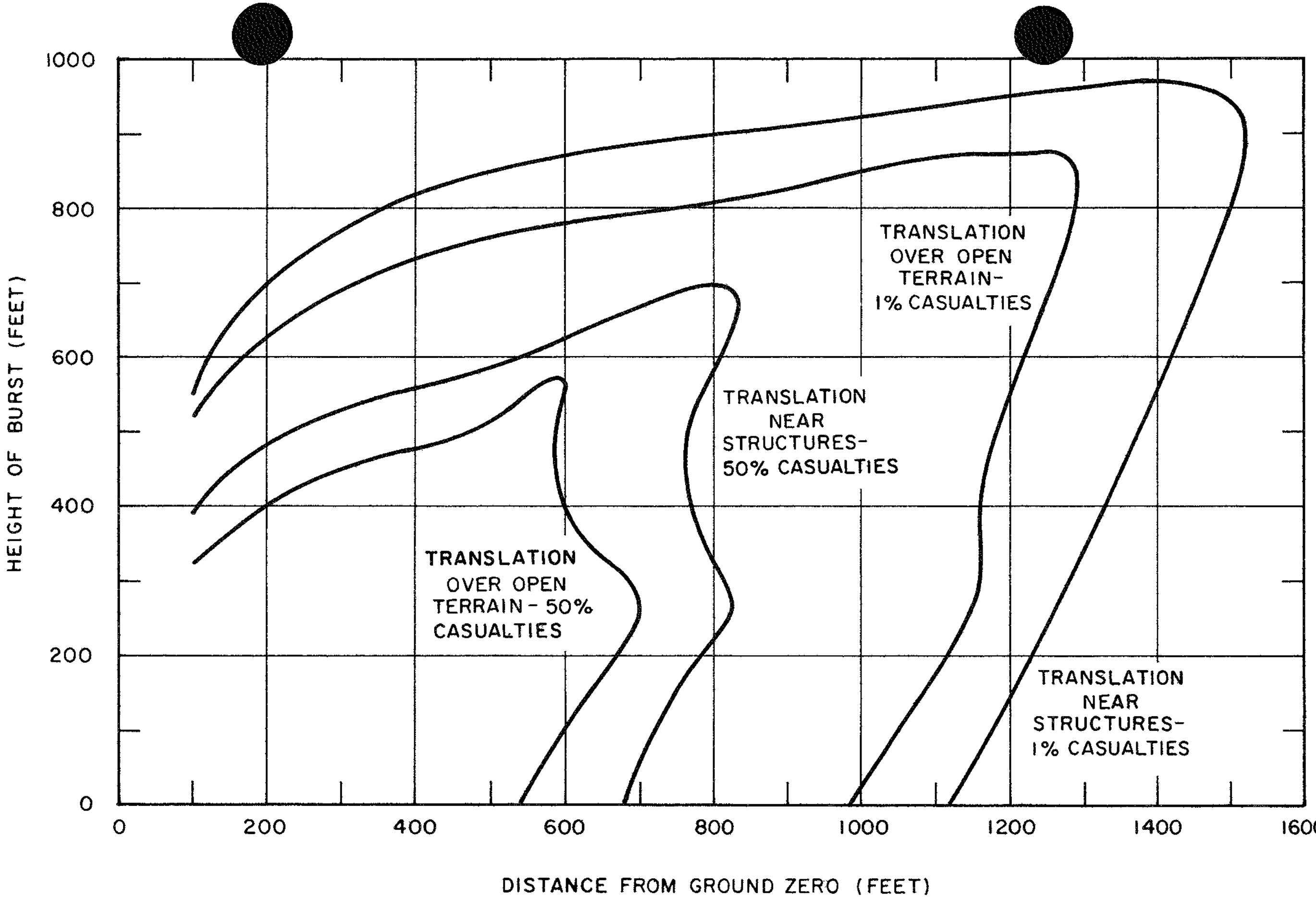

Figure 12.49. Casualties from translation near structures and over open terrain for a 1-kiloton explosion. (The curves for open terrain are more approximate than the others.)

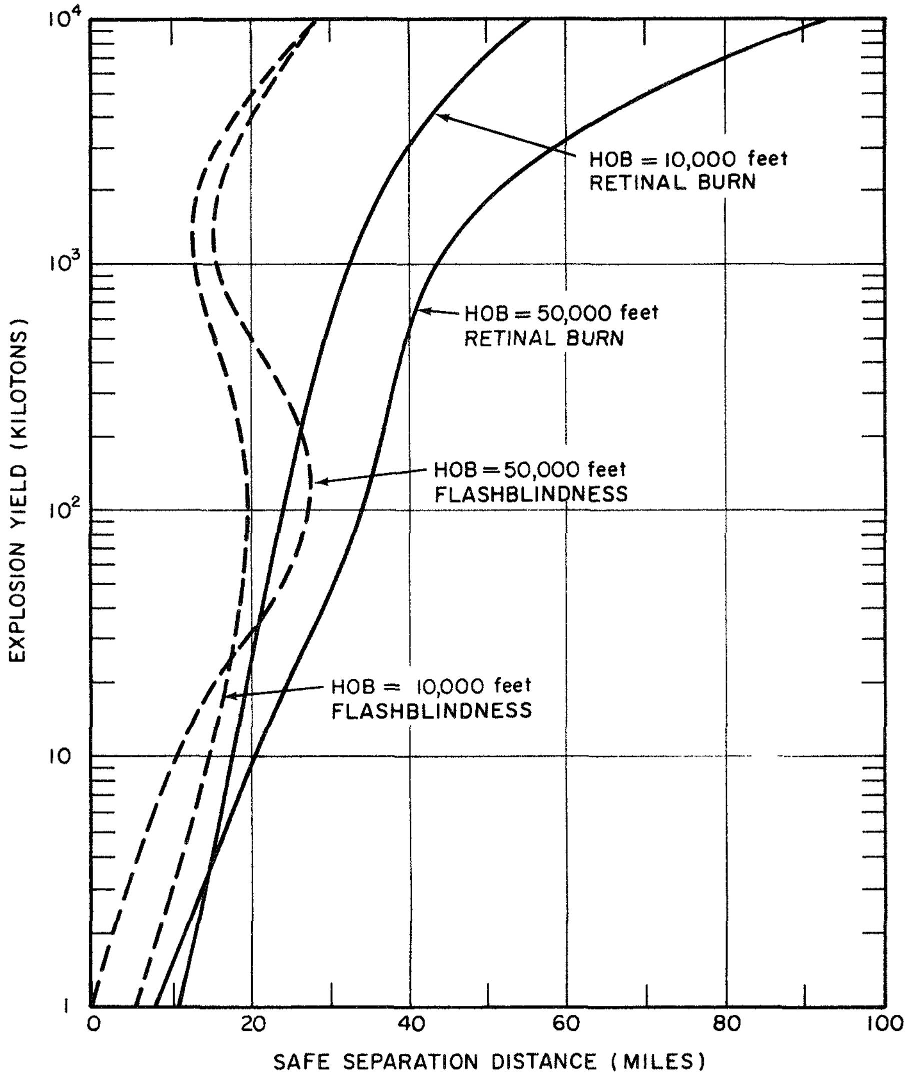

Figure 12.88a. Flashblindness and retinal burn safe separation distances for an observer on the ground, as a function of explosion yield, for burst heights of 10,000 feet and 50,000 feet on a clear day.

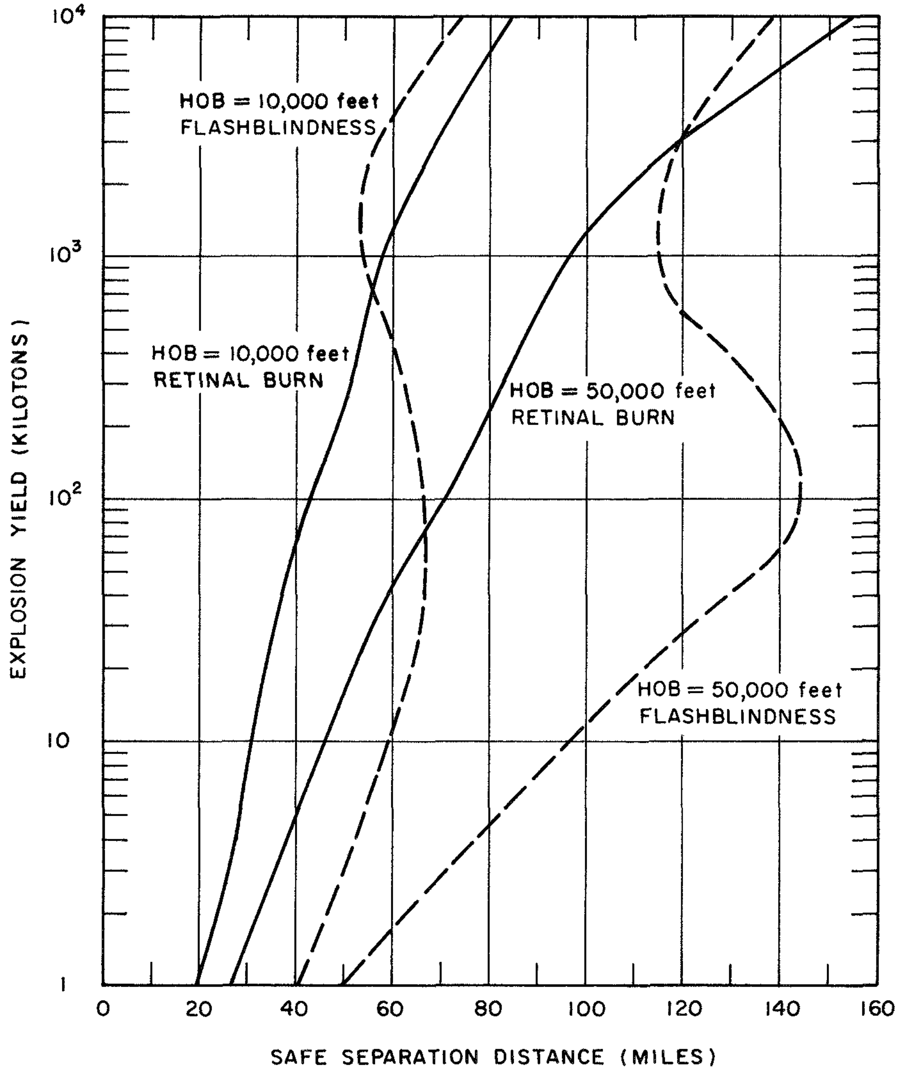

Figure 12.88b. Flashblindness and retinal burn safe separation distances for an observer on the ground, as a function of explosion yield, for burst heights of 10,000 feet and 50,000 feet at night.

Table 12.108

SUMMARY OF CLINICAL EFFECTS OF ACUTE IONIZING RADIATION DOSES

Range	0 to 100 rems Subclinical range	100 to 1,000 rems Therapeutic range			Over 1,000 rems Lethal range	
		100 to 200 rems	200 to 600 rems	600 to 1,000 rems	1,000 to 5,000 rems	Over 5,000 rems
		Clinical surveillance	Therapy effective	Therapy promising	Therapy palliative	
Incidence of vomiting	None	100 rems infrequent 200 rems common	300 rems 100%	100%	100%	
Initial Phase Onset Duration	 — —	 3 to 6 hours ≤ 1 day	 ½ to 6 hours 1 to 2 days	 ¼ to ½ hour ≤ 2 days	 5 to 30 minutes ≤ 1 day	 Almost immediately**
Latent Phase Onset Duration	 — —	 ≤ 1 day ≤ 2 weeks	 1 to 2 days 1 to 4 weeks	 ≤ 2 days 5 to 10 days	 ≤ 1 day* 0 th 7 days*	 Almost immediately**
Final Phase Onset Duration	 — —	 10 to 14 days 4 weeks	 1 to 4 weeks 1 to 8 weeks	 5 to 10 days 1 to 4 weeks	 0 to 10 days 2 to 10 days	 Almost immediately**
Leading organ	Hematopoietic tissue				Gastrointestinal tract	Central nervous system
Characteristic signs	None below 50 rems	Moderate leukopenia	Severe leukopenia, purpura, hemorrhage, infection Epilation above 300 rems		Diarrhea, fever, disturbance of electrolyte balance	Convulsions, tremor, ataxia, lethargy
Critical period post-exposure	—	—	1 to 6 weeks		2 to 14 days	1 to 48 hours

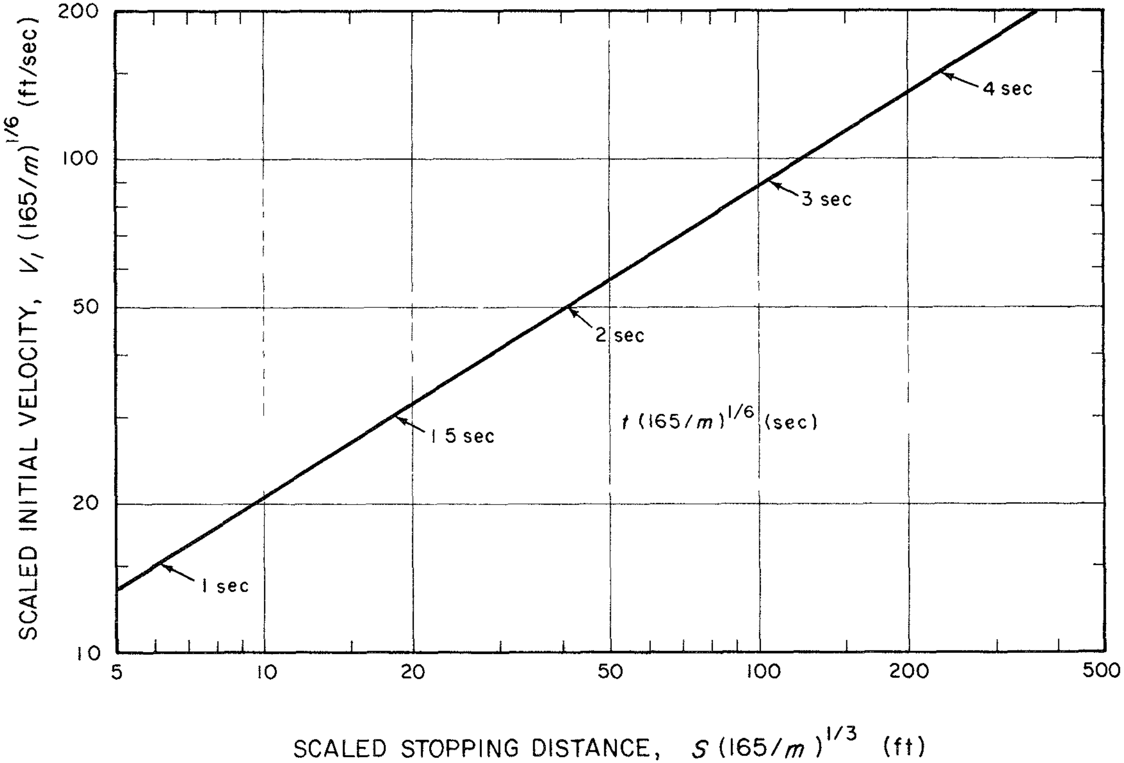

Figure 12 239. Initial velocity of animal (V_I feet per second) scaled according to the mass (in pounds) versus the stopping distance for decelerative tumbling on a hard, flat surface. Scaled stopping times are indicated on the plot. (Estimated accuracy ± 10 to 15 percent.)

except that the latter are soon visible whereas the effects of beta particles may not be seen for three or four weeks.

12.246 The damage to the cattle at the TRINITY site was described as the development of zones of thickened and hardened skin which appeared as plaques and cutaneous horns. After 15 years, three of the exposed cows developed scale-like carcinomas of the skin in the affected regions, but it is not entirely clear that they were induced by radiation. In areas less severely affected, there was some loss and graying of the hair. The location of these cattle with respect to ground zero is not known, but it is estimated that the whole-body gamma radiation dose was about 150 rems, although the skin dose may have been very much larger. There was no evidence of radiation damage on the lower surfaces of the body that might have been caused by exposure from fallout on the ground.

12.247 Information concerning the possible effects of fallout on farm animals under various conditions has been obtained from studies with simulated fallout sources. Three main situations of interest, depending on the location of the animals, are as follows:

1. In a barn: whole-body exposure to gamma rays from fallout on the roof and the surrounding ground.
2. In a pen or corral: whole-body exposure to gamma rays from fallout on the ground and exposure of the skin to beta particles from fallout deposited on the skin.
3. In a pasture: whole-body exposure to gamma rays from fallout on the ground, exposure of the skin to beta particles, and exposure of the gastrointestinal tract from fallout on the grass.

The exposure to gamma rays is simulated by means of an external cobalt-60 source. Skin irradiation is achieved by attaching to the back of the animal a flexible source of beta particles. Finally, the internal exposure is simulated by adding to the animal's feed a material consisting of yttrium-90 fused to 88–175 micrometers particles of sand, giving a specific activity of 10 microcuries per gram of sand. This product is considered to be representative of the beta radiation from the fallout produced by a land-surface detonation.

12.248 Observations have been made on animals exposed to whole-body gamma radiation alone (barn) or in combination with skin exposure (pen or corral) or with exposure of the skin and the intestinal tract (pasture) at dose rates

Table 12.248

ESTIMATED LIVESTOCK LETHALITY ($LD_{50/60}$) FROM FALLOUT

Total Gamma Exposure (roentgens)

Animals	Barn	Pen or Corral	Pasture
Cattle	500	450	180
Sheep	400	350	240
Swine	640	600*	550*
Horses	670	600*	350*
Poultry	900	850*	800*

*No experimental data available; estimates are based on grazing habits, anatomy, and physiology of the species.

possible synergism with gamma radiation is very sparse.

12.265 Food crops harvested from plants that have survived exposure to fallout would probably be safe to eat under emergency conditions, especially if the exposure occurred during the later stages of growth. Care would have to be taken to remove by washing any fallout particles that might be attached to leaf or root vegetables The major problem would arise from the possible presence in the edible parts of the plant of radionuclides taken up from the soil by the roots or from particles deposited on the leaves. Because of the complexities involved, no generalizations can be made and each situation would have to be evaluated individually.

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